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Transport Properties of Liquid and Gaseous D₂O over a Wide Range of Temperature and Pressure[a]

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Data for the viscosity and thermal conductivity of dense gaseous and liquid heavy water (D₂O) have been reviewed and critically evaluated. Selected data were fitted to equations, from which tables of values were generated from temperatures up to 500 °C and for pressures up to 100 MPa for the viscosity and up to 550 °C and 100 MPa for the thermal conductivity. The uncertainties of the tabular values were estimated. The present paper is intended to explain the background of the International Representations of the Viscosity and Thermal Conductivity of Heavy Water Substance of the International Association for the Properties of Steam. With the aid of the present correlations, the kinematic viscosity, thermal diffusivity, and Prandtl number have been calculated. The present status of the gaseous diffusion coefficient is also briefly reviewed.

Key words: critically evaluated data; deuterium oxide; diffusion coefficient; heavy water; kinematic viscosity; Prandtl number; thermal conductivity; thermal diffusivity; transport properties; viscosity.

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1. Introduction

Since heavy water is one of the most important substances in nuclear power technology, information on the thermophysical properties of heavy water over wide ranges of temperature and pressure is needed for successful design.

After the publication of the comprehensive compilation of the properties of heavy water[1] in 1964, no comprehensive critical review of the transport properties was published for many years. Having collected a large body of experimental data published since 1964, the present authors reported the data and correlations for the viscosity and the thermal conductivity of heavy water[2-4] to the International Association for the Properties of Steam.

Figures 1 and 2 illustrate the recent achievements regarding viscosity. Figure 1 shows the region of the viscosity data covered in Ref. 1, and Fig. 2 shows the range of the data that appeared after 1964. This convinced the authors that a comprehensive compilation and a critical evaluation of the thermophysical properties of heavy water were now called for. The thermodynamic properties had already been studied and results were crystalized in the form of an equation of state formulated by Hill, MacMillan, and Lee.[E1-E5]

The present study was intended to compile available data and to describe the present status of our knowledge on the transport properties of heavy water. The collected data were evaluated and a set of selected data was then used as a basis to develop equations for the viscosity and the thermal

FIGURE 2. Experimental studies of viscosity of D_2O (after 1963).

FIGURE 1. Experimental studies of viscosity of D_2O (prior to 1963).

conductivity. These equations are valid over wide ranges of temperature and pressure, both in the liquid and the gaseous phase. The most probable values of these two properties are listed in tables. Several derived properties are also given. Finally, the present status of the gaseous diffusion coefficient is reviewed.

The primary purpose of this survey paper, which was written at the request of the Executive Committee of the International Association for the Properties of Steam, is to document the sources and analysis which led to the adoption of the Release on Viscosity and Thermal Conductivity of Heavy Water Substance of 1982. This document defines the *International Representation of the Viscosity of Heavy Water Substance, 1982* and the *International Representation of the Thermal Conductivity of Heavy Water Substance, 1982*. It was stipulated that the two international representations should use temperature and density as independent variables and that they should be tied to Hill's equation of state[E3-E5] for the calculation of density when the pressure is chosen as the independent variable. For this reason, the international representations are limited to a maximum pressure of 100 MPa.

However, in the course of the analysis it became clear that it is possible to extend the correlation to higher pressures. In the case of viscosity, the validity of the formulation may be extended to a pressure of 200 MPa at temperatures below 473 K (200 °C). In the case of thermal conductivity,

calculations were made to a pressure as high as 250 MPa and compared with the measurements of Refs. T23 and T27. However, such an extension in range made it necessary to calculate densities at pressures in excess of 100 MPa from a different source.

The extension of the pressure range beyond that originally intended achieves two purposes. First, it demonstrates that the internationally adopted representations may be safely extrapolated in pressure. Secondly, even though not sanctioned by international agreement, the reader has at his disposal values of the transport properties in the maximum range covered by existing, measured data.

2. Isotopes of Heavy Water and the Effect of Isotopic Impurities

There exist three isotopes of hydrogen, namely, ^1H, ^2H(deuterium, D), and ^3H(tritium, T). Similarly, there exist three isotopes of oxygen: ^{16}O, ^{17}O, and ^{18}O. The natural abundance of oxygen isotopes in mole fraction is[5]: ^{16}O: 99.759%, ^{17}O: 0.037%, and ^{18}O: 0.204%. Therefore, there exist several kinds of water, but the term "heavy water" usually means a natural mixture of $D_2{}^{16}O$, $D_2{}^{17}O$, and $D_2{}^{18}O$. Even though sometimes this term is used for pure $D_2{}^{16}O$, the difference between them makes a negligible effect on the transport properties, since $D_2{}^{17}O$ and $D_2{}^{18}O$ are present only as traces. Commercially available heavy water often contains 99.8% $D_2{}^{16}O$, the rest being mostly $H_2{}^{16}O$. In the case of the transport properties, the effect of this impurity is estimated to be much smaller than experimental uncertainties and no corrections for it are needed.

3. Preliminary Considerations Regarding the Selection of Experimental Data

3.1. Effect of Different Temperature Scales

In 1968, the new International Practical Temperature Scale, IPTS-68, was introduced and the former scale, IPTS-48, became obsolete. Therefore, all data prior to the year 1968 and, possibly some data after that year, correspond to IPTS-48.

The differences between the two temperature scales increase with increasing temperature and reach 0.07 K at the critical temperature of D_2O (643.89 K) and 0.67 K at 1073 K (800 °C), the highest temperature at which the selected experimental data are available.

Considering the result of Watson, Basu, and J. V. Sengers[6] concerning the viscosity of ordinary water, it is clear that the difference between the IPTS-48 and the IPTS-68 affects the viscosity values at most 0.05%, except in the very narrow region where the critical enhancement is significant. No adjustment for the temperature scales was applied in the case of the viscosity.

In the case of thermal conductivity, the critical enhancement appears much more significant than in the case of viscosity, and the effect of the difference of the IPTS-48 and the IPTS-68 may become large in the critical region. Fortunately, the bulk of the data in this region were of recent origin and are presumed to be based on IPTS-68. In other

regions, the effect of the different temperature scales is expected to be much smaller.

3.2. Effect of Different Density Sources

In order to perform a successful correlation of transport properties, it is necessary to examine carefully the available sources of density. We assumed that the revised correlation of Hill, MacMillan, and Lee[E3–E5] is completely reliable. However, this correlation extends only to a pressure of 100 MPa, which is adequate for the purpose of the international standard, but does not permit us to analyze the rather abundant data on transport properties which were measured at higher pressures.

The first thought is to use the classical law of corresponding states with respect to light water at pressures exceeding 100 MPa. A comparison with available measured values of density in that range shows, however, that introduction of a simple correction function,

$$f_c(T) = 0.996\,14 + 5.0007 \times 10^{-5}T - 5.9643 \times 10^{-8}T^2 \quad (1)$$

is required. The density of heavy water is then calculated from

$$\rho = f_c(T) \cdot \rho_{cs}. \quad (2)$$

where ρ_{cs} is the density estimated by the law of corresponding states from the density of light water as represented by the equation of state by Pollak.[7]

A knowledge of the density of heavy water is needed not only for the correlation but also for the analysis of viscosity. Many investigators employed capillary viscometers in their experiments. Since this type of instrument actually measures the kinematic viscosity, values of density are needed to calculate the dynamic viscosity. However, an accurate equation of state for heavy water valid in wide ranges of pressure and temperature, reaching into the vicinity of the critical point, was not available at the time the measurements were made. Consequently, some experimentalists were compelled to estimate densities and as a result the values used by different authors are not mutually consistent and not always reliable.

Since we now have confidence in the equation of Refs. E3–E5 up to 100 MPa and in the corrected law of corresponding states beyond that, a rational reevaluation of the primary viscosity data became possible whenever the author of the measurement published his adopted density as well as the kinematic viscosity. But, unfortunately, some authors did not report such information and the reevaluation then became impossible.

3.3. Effect of Different Reference Data used for Calibrating the Instruments

Some experimental data were obtained on a relative basis. For these measurements, the data for the standard substances used for calibrating the apparatus must be critically reviewed.

In the case of thermal conductivity, the numbers and ranges of relative measurements are limited, and for them the problem is not serious. However, in the case of the viscosity, most data were obtained in capillary viscometers calibrated with light water. The presently accepted best reference value for ordinary water is 1.002×10^{-4} Pa·s at 293.15

K (20 °C) and 0.101 325 MPa (1 atm). The reference value which was often used until about 1950 was 1.005×10^{-4} Pa·s as stipulated, for example, in the International Critical Tables. This exceeds the preceding value by 0.3%. Since no important data were published before 1950 for the viscosity of D_2O, no correction was applied in the present study.

3.4. Conversion into SI Units

Some earlier experimental data are given in units other than SI. Therefore a conversion into SI units became necessary. When one converts data into SI, the difficulty lies in those for the thermal conductivity. Earlier data are usually expressed in cal/(m·s·K) or in cal/(m·h·K). Several different definitions for the unit "calorie" exist, but in most papers the authors did not specify which calorie they had employed. We assumed that the unit cal_{15} ($1 cal_{15} = 4.1855$ J) was most widely used. The difference between the calories of the other kinds and cal_{15} is at most 0.1%. This is much smaller than the experimental uncertainty of thermal conductivity measurements, even of the best quality. Consequently, the conversion factor of 1 cal $= 4.1855$ J was used throughout.

4. Viscosity

4.1. Available data

Experimental data of the viscosity are found in Refs. V1–V32. Some references repeatedly list the same data.

a. General Explanation

The measurement of the viscosity of heavy water started very soon after its discovery. The experimental studies of the viscosity of heavy water are listed in Tables 1–4 in chronological order. Most of them employed the capillary method. The oscillating disk method, the rolling ball method, and the falling body method were also used.

Experimental data are available in very wide ranges of temperature and pressure, namely, from the melting point (277 K) to 1773 K and up to about 500 MPa. Most of these data were obtained after 1970. Figure 1 shows the region where the viscosity data were available in 1963.[1] Figure 2 shows the region of the data which appeared after the publi-

cation of Ref. 1. In 1963 there existed only one set of data in the high pressure liquid region. No data were available in the high pressure vapor region or in the critical region.

An examination of Figs. 1 and 2 and of the references convinced us that an adequate body of data existed for a correlation at atmospheric pressure in the vapor region and over the whole field in the liquid region. As far as the high pressure vapor region is concerned, ample data are also available at its upper end, data in the intermediate range being scarce. Nevertheless, a reasonable correlation bridging this gap proved to be possible.

b. Liquid Phase

The data for the liquid at atmospheric pressure are listed in Table 1. The earliest study was published almost fifty years ago. The numerical values agree well with one another, except for a single value by Selwood and Frost (1933)[V1] and the set due to Lemonde (1941).[V6] Selwood and Frost's value[V1] was too high due to a fault in the viscometer calibration. This was later corrected.[V2]

The data for the liquid at high pressure are listed in Table 2. Among them, the first two sets, namely, those of Hardy and Cottington (1949)[V7,V8] and Heiks, Barnett, Jones, and Orban (1954)[V10] were obtained along the saturation line. The first study of the pressure effect on the viscosity was carried out by Timrot and Shuiskaya (1959).[V12] These data show reasonable agreement with one another, except for those by Heiks et al. (1954),[V10] Timrot and Shuiskaya (1959),[V12] and Lee and Jonas (1972).[V21]

Heiks et al.[V10] measured the viscosity of saturated heavy water using a falling body viscometer. The results were obtained as ratios of the viscosities of heavy water to ordinary water and calculated with the aid of data for ordinary water, Jaumotte (1951).[8] These have proved to be inaccurate when compared with recent data. A reevaluation with the aid of the latest data for ordinary water also gave disappointing results. Timrot and Shuiskaya[V12] obtained their results using an unconventional capillary viscometer characterized by excessive scatter. The work by Lee and Jonas[V21] was not organized to obtain accurate values of viscosity but

Table 1. Measurements of the viscosity of heavy water
(liquid, atmospheric pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Selwood,P.W.	1933	Liq.		293.15	0.1(atmospheric)	92	V1
Lewis,G.N.	1933	Liq.	Capillary	278.15 - 308.15	0.1(atmospheric)	90	V3
Taylor,H.S.	1934	Liq.		293.15	0.1(atmospheric)		V2
Baker,W.N.	1935	Liq.	Capillary	298.15	0.1(atmospheric)	98.0	V4
Jones,G.	1936	Liq.	Capillary	298.15	0.1(atmospheric)	97.6	V5
Lemonde,H.	1941	Liq.	Capillary	277.15 - 293.15	0.1(atmospheric)	99.65	V6
Hardy,R.C.	1949	Liq.	Capillary	278.15 - 398.15	0.343	99.5	V7,V8
Heiks,J.R.	1954	Liq.	Falling body	303.15 - 523.15	4.00(saturation)	99.20	V10
Agayev,N.A.*	1968	Liq.	Capillary	277.15 - 423.15	117.8	99.8	V14,V15,V17
Selecki,A.*	1970	Liq.	Capillary	298.15 - 363.15	0.1(atmospheric)	99.8	V19
Millero,F.J.*	1971	Liq.	Capillary	278.15 - 343.15	0.1(atmospheric)	99.88	V20
Agayev,N.A.*	1971	Liq.	Capillary	373.15 - 548.15	117.8	99.8	V16,V17
Kellomaki,A.*	1975	Liq.	Capillary	283.15 - 308.15	0.1(atmospheric)	99.8	V31
Goncalves,F.A.*	1978	Liq.	Capillary	293.15 - 333.15	0.1(atmospheric)	99.75	V32
Agayev,N.A.*	1979	Liq.&Vap.	Capillary	277.01 - 644.65	196.2	99.8	V18

Table 2.   Measurements of the viscosity of heavy water
(liquid, high pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Hardy,R.C.	1949	Liq.	Capillary	278.15 - 398.15	0.343	99.5	V7,V8
Heiks,J.R.	1954	Liq.	Falling body	303.15 - 523.15	4.00(saturation)	99.20	V10
Timrot,D.L.	1959	Liq.	Capillary	288.35 - 561.15	31.9		V12
Agayev,N.A.*	1968	Liq.	Capillary	277.15 - 423.15	117.8	99.8	V14,V15,V17
Agayev,N.A.*	1971	Liq.	Capillary	373.15 - 548.15	117.8	99.8	V16,V17
Lee,Y.	1972	Liq.	Rolling ball	283.15 - 363.15	467.5	99.8	V21
Rivkin,S.L.*	1972	Liq.&Vap.	Capillary	473.15 - 648.15	50.0	99.98	V22
Rivkin,S.L.*	1974	Liq.&Vap.	Capillary	473.15 - 648.15	50.0		V23
Rivkin,S.L.*	1974	Liq.&Vap.	Capillary	323.15 - 448.15	50.0		V24-V26
Kinoshita,H.*	1978	Liq.&Vap.	Capillary	&673.15 - 773.15 323.15 - 773.10	78.5	99.87	V28,V29
Agayev,N.A.*	1979	Liq.&Vap.	Capillary	277.01 - 644.65	196.2	99.8	V18

to investigate the effect of density on the structure of heavy water. The viscometer was of the rolling ball type. It was calibrated at atmospheric pressure with the aid of the experimental results of Agayev and Yusibova (1968).[V15]

We excluded the above three sets of data and based our correlation at temperatures above 398 K (125 °C) on three groups, namely, the results from three centers. In particular, we included the papers by Agayev and Yusibova (1968),[V14,V15,V17] Agayev, Kerimov, and Abas-zade (1971),[V16,V17] Rivkin, Levin, Izrailevskii, and Kharitonov (1972),[V22] Rivkin, Levin, Izrailevskii, and Kharitonov (1974a),[V23] Rivkin, Levin, Izrailevskii, and Kharitonov (1974b),[V24-V26] and Kinoshita, S. Abe, and Nagashima (1978).[V28,V29] The agreement among these data sets is, as mentioned before, generally good, but at temperatures above about 473 K (200 °C), the data by Agayev and co-workers[V16,V17] tend to be higher than those of the other two groups.

c. Gaseous Phase

Only five sets of data are available for vapor at atmospheric pressure as shown in Table 3.

The first set of data for the vapor at pressures around atmospheric are of Rowlinson (1953)[V9] who employed a capillary viscometer. These data are given as ratios of the viscosity of heavy water vapor to that of steam (vapor of ordinary water). There is no information about the pressures at which the measurements were carried out.

The data by Bonilla, Wang, and Weiner (1956)[V11] were also obtained by means of a capillary viscometer and the apparatus was calibrated with nitrogen gas. Bonilla, Wang, and Weiner[V11] used Vasilesco's viscosity values[9] as a calibrating standard, but these are considered incorrect now. However, Bonilla's ratios of the viscosities of the vapors of heavy water and ordinary water seemed to be worthy of consideration.

The data by Timrot, Serednitskaya, and Bespalov (1974)[V13] were obtained by means of an oscillating disk viscometer. These measurements are considered to be among the most precise in this region. S. Abe, Fujioka, and Nagashima (1978)[V30] studied the viscosity of heavy water vapor at pressures from about 0.6 MPa to near-saturation pressure and the results were extrapolated to atmospheric pressure. The extrapolated values agree very well with the experimental results of Timrot, Serednitskaya, and Bespalov.[V13]

Agayev (1979)[V18] also studied the effect of pressure on the viscosity of heavy water vapor using a capillary viscometer. At atmospheric pressure, only two data points were obtained, one at 423 K (150 °C) and the other at 448 K (175 °C). These two and the others at higher temperatures and pressures but extrapolated to atmospheric pressure also agree fairly well with those of Timrot and of S. Abe.

The data of Rivkin, Levin, Izrailevskii, Kharitonov, and Romashin (1979)[V27] should be discussed here, even though they are not listed in Table 3. Rivkin and co-workers[V27] measured the viscosity of heavy water vapor at pressures from 2 MPa to about saturation. An extrapolation

Table 3.   Measurements of the viscosity of heavy water
(vapor, atmospheric pressure)

First author	Year	State	Method	Temperature range (K)	Maximum Pressure (MPa)	Purity(%)	Ref.no.
Rowlinson,J.S.	1953	Vap.	Capillary	353.0 - 405.0	< 0.1		V9
Bonilla,C.F.	1956	Vap.	Capillary	473.15 -1773.15	0.1(atmospheric)	99.8	V11
Timrot,D.L.*	1974	Vap.	Oscillating disk	374.95 - 777.95	0.127	99.5	V13
Abe,S.*	1978	Vap.	Capillary	473.14 - 673.25	19.68	99.8	V30
Agayev,N.A.*	1979	Liq.&Vap.	Capillary	277.01 - 644.65	196.2	99.8	V18

Table 4. Measurements of the viscosity of heavy water
(vapor, high pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Rivkin,S.L.*	1972	Liq.&Vap.	Capillary	473.15 - 648.15	50.0	99.98	V22
Rivkin,S.L.*	1974	Liq.&Vap.	Capillary	473.15 - 648.15	50.0		V23
Rivkin,S.L.*	1974	Liq.&Vap.	Capillary	323.15 - 448.15 &673.15 - 773.15	50.0		V24-V26
Kinoshita,H.*	1978	Liq.&Vap.	Capillary	323.15 - 773.10	78.5	99.87	V28,V29
Abe,S.*	1978	Vap.	Capillary	473.14 - 673.25	19.68	99.8	V30
Agayev,N.A.*	1979	Liq.&Vap.	Capillary	277.01 - 644.65	196.2	99.8	V18
Rivkin,S.L.	1979	Vap.	Capillary	523.15 - 643.15	21.44		V27

of Rivkin's data[V27] to atmospheric pressure gives values 2% or 3% higher than the direct data of Timrot and co-workers[V13] and the extrapolated data of S. Abe and co-workers[V30] and of Agayev.[V18]

In the correlation, we used the data by Timrot, Serednitskaya, and Bespalov,[V13] by S. Abe, Fujioka, and Nagashima,[V30] and by Agayev.[V18]

Only seven sets of data are available for the vapor at high pressures. They are listed in Table 4. At subcritical temperatures, the pressure effect on the viscosity of heavy water vapor was first examined by S. Abe, Fujioka, and Nagashima (1978)[V30] who employed a capillary viscometer. They were the first to confirm the negative pressure effect on the viscosity of heavy water vapor which is analogous to that observed in the viscosity of ordinary steam.

Agayev (1978)[V18] and Rivkin, Levin, Izrailevskii, Kharitonov, and Romashin (1978)[V27] also studied the effect of pressure on the viscosity of heavy water vapor by means of capillary viscometers. The results of Agayev[V18] are in fair agreement with those of S. Abe and co-workers,[V30] although the negative pressure effect of Agayev's data is slightly less pronounced than that of S. Abe's data.[V30] The results of Rivkin and co-workers[V27] are, as mentioned before, higher than those of S. Abe and co-workers[V30] and of Agayev.[V18] Furthermore, the pressure dependence of Rivkin's data shows a steeper increase at pressures near saturation compared to that of S. Abe's and Agayev's data.

At supercritical temperatures, four sets of data are available, namely, those of Rivkin, Levin, Izrailevskii, and Kharitonov (1972),[V22] of Rivkin, Levin, Izrailevskii, and Kharitonov (1974a),[V23] of Rivkin, Levin, Izrailevskii, and Kharitonov (1974b),[V24-V26] and of Kinoshita, S. Abe, and Nagashima (1978).[V28,V29] A comparison of Rivkin's and Kinoshita's results is possible only at 648, 673, and 773 K (375, 400, and 500 °C). At 648 K (375 °C), the agreement is good. At 673 K (400 °C) and at pressures lower than 40 MPa, the agreement is disappointing. The data by Rivkin are much higher than those by Kinoshita. This means that the negative pressure effect appears much stronger in the latter in this region. At higher pressures, and at 773 K (500 °C), the agreement is good.

d. Critical Region

Data near the critical point were published by only three groups of authors. These include Rivkin, Levin, Izrai-

levskii, and Kharitonov (1972),[V22] Rivkin, Levin, Izrailevskii, and Kharitonov (1974a),[V23] Kinoshita, S. Abe, and Nagashima (1978)[V28,V29] for subcritical liquid and supercritical dense-gas regions, and Rivkin, Levin, Izrailevskii, Kharitonov, and Romashin (1979)[V27] and Agayev (1979)[V18] for subcritical vapor region.

When analyzing the data in this region, we encountered two problems. One is the uncertainty in the density employed by each author. In the critical region, the difference between the density values taken from different sources is very large; for instance, Rivkin[V27] used the density value of 261.1 kg/m^3 at 643.15 K (370.0 °C) and at 21.468 MPa, whereas the latest version of the equation of state by Hill et al.[E3-E5] gives 288.6 kg/m^3 at the same conditions. The difference between the density values is as much as 10%, and the recalculated viscosity data at this point would also be increased by 10%. The greatest difficulty resides in Agayev's data,[V18] for which no values of measured kinematic viscosity or density employed for reducing the experimental results are given. Though the source of the density values is specified as the equation of state given in Ref. 1, the equation must be considered invalid in the close vicinity of the critical point, related to Agayev's results. Furthermore, the temperatures and pressures given in Agayev's paper appear to be rounded. Therefore, it becomes impossible to ascertain what values of density he used. For this reason, the uncorrected original viscosity values were adopted for the fit.

The second problem is the presence of a critical enhancement. According to Rivkin's experimental study,[V24] there exists a critical enhancement in the viscosity of light water, though it is much weaker than that for the thermal conductivity. Therefore it is reasonable to think that a similar critical enhancement must exist in the viscosity of heavy water. However, the critical enhancement for the viscosity appears only in the very small region around the critical point, namely,

$$0.977 T_c < T < 1.023 T_c,$$

and

$$0.75 \rho_c < \rho < 1.25 \rho_c$$

(according to Watson and co-workers[6]). In the case of heavy water, only Agayev's measurements are inside this region.

4.2. Equation for the Viscosity of Heavy Water

a. Preliminary Considerations

A single existing representation for the viscosity of heavy water valid for a wide range of temperature and pressure was earlier formulated by the present authors.[2,3] Even though that formulation reproduced the experimental viscosity of heavy water in the temperature range from the melting point to 773 K and in the pressure range up to 100 MPa, it was not suitable for extrapolation to higher pressures or higher temperatures. Therefore, it became necessary to adopt a new form in order to base it on the latest data.

There are two alternative choices for the equation: one is to express the excess viscosity $\eta(\rho,T) - \eta_0(T)$ as a function of the density and temperature,

$$\eta(\rho,T) = \eta_0(T) + \Delta\eta(\rho,T), \tag{3}$$

where $\eta_0(T)$ is the viscosity at a sufficiently low density. The other possibility is to correlate the ratio $\eta(\rho,T)/\eta_0(T)$ as

$$\eta(\rho,T) = \eta_0(T) \cdot F(\rho,T). \tag{4}$$

The first equation for the viscosity of heavy water published by the present authors adopted the form of Eq. (3). Watson, Basu, and Sengers[6] compared various forms of equations in their work of ordinary water and concluded that the form of Eq. (4), as modified below, is very convenient. Thus, we based the present correlation on the form

$$\eta(\rho_r,T_r) = \eta_0(T_r)\exp\left[\rho_r\left\{\sum_i\sum_j a_{ij}(T_r^{-1}-1)^i(\rho_r-1)^j\right\}\right], \tag{5}$$

where, $T_r = T/T_c$ and $\rho_r = \rho/\rho_c$, and so secured consistency with the preceding equation for ordinary water.

b. Sources for the Pseudocritical Constants and Density

In order to introduce reduced values into Eq. (5), it is not really convenient to work with the most probable critical parameters of the real substance, because these are subject to future, or even frequent, revision. It is best to interpret the reference values as convenient, arbitrary constants, even though we assign to them values close to the critical temperature and density following the example set by Watson et al. Thus we assume

$$T_c = 643.89 \text{ K} \quad \text{and} \quad \rho_c = 358 \text{ kg/m}^3,$$

to achieve consistency with Hill's equation of state.[E3-E5]

In our calculations of density, we employed the latest version of the equation of state of Hill and his co-workers.[E3-E5] Hill's equation is valid in the temperature range up to 873 K (600 °C) and in the pressure range up to 100 MPa. The density values outside this region were estimated by means of the corresponding states principle with H_2O as the reference substance, as explained in Sec. 3.2.

c. Selected Experimental Data

Considering the analysis in Sec. 4.1, the following sets of data were used as the reference data for the present correlation.

Liquid region:
Agayev and co-workers[V14-V18]
Selecki, Tyminski, and Chmielewski[V19]
Millero, Dexter, and Hoff[V20]
Rivkin and co-workers[V22-V26]
Kinoshita, Abe, and Nagashima[V28,V29]
Kellomäki[V31]
Gonçalves[V32]

Vapor region:
Timrot, Serednitskaya, and Bespalov[V13]
Agayev[V18]
Rivkin and co-workers[V22-V26]
Kinoshita, Abe, and Nagashima[V28,V29]
Abe, Fujioka, and Nagashima[V30]
These are distinguished by asterisks in Tables 1–4.

At temperatures above 900 K, estimates of viscosity were based on the hypothesis that the excess viscosity is a function of density alone, in analogy with ordinary water. This hypothesis enables us also to extrapolate the present equation to higher temperatures.

d. Correlated Equation for the Viscosity

The result of the correlation is the equation:

$$\eta = \eta_0(T_r)\cdot\exp\left\{\rho_r\left[\sum_{i=0}^{5}\sum_{j=0}^{6} A_{ij}(T_r^{-1}-1)^i(\rho_r-1)^j\right]\right\}, \tag{6}$$

where

$$\eta_0(T_r) = H\cdot T_r^{1/2}\left(\sum_{k=0}^{3} B_k\cdot T_r^{-k}\right)^{-1}. \tag{6a}$$

The reduced variables are

$$T_r = T/T_c \quad \text{and} \quad \rho_r = \rho/\rho_c, \tag{6b}$$

and the meaning of the symbols is as follows:

η—viscosity T_c—pseudocritical temperature
T—temperature ρ_c—pseudocritical density
ρ—density

The constants appearing in Eqs. (6), (6a), and (6b) are listed below.

$T_c = 643.89$ K,

$\rho_c = 358$ kg/m³,

$H = 55.2651\times10^{-6}$ Pa·s.

The coefficients A_{ij} in Eq. (6)

$i =$	0	1	2	3	4	5
$j = 0$	0.4864 192	− 0.2448 372	− 0.8702 035	0.8716 056	− 1.0511 26	0.3458 395
1	0.3509 007	1.3154 36	1.2977 52	1.3534 48	0.0	0.0
2	− 0.2847 572	− 1.0370 26	− 1.2878 46	0.0	0.0	− 0.0214 8229
3	0.0701 3759	0.4660 127	0.2292 075	− 0.4857 462	0.0	0.0
4	0.0164 1220	− 0.0288 4911	0.0	0.1607 171	0.0	− 0.0096 0384 6
5	− 0.0116 3815	− 0.0082 3958 7	0.0	0.0	0.0	0.0045 5991 4
6	0.0	0.0	0.0	− 0.0038 8665 9	0.0	0.0

The coefficients B_k in Eq. (6)

$B_0 =$	1.0000 0
$B_1 =$	0.9406 95
$B_2 =$	0.5783 77
$B_3 =$	− 0.2020 44

Equation (6a) is identical with that proposed recently by Watson.[10] Due to a stronger temperature dependence of the viscosity of heavy water at the lowest temperatures, the number of terms in Eq. (6) is larger than that of Watson, Basu, and Sengers.[6] Watson, Basu, and Sengers[6] formulated a separate equation for the critical enhancement of the viscosity of ordinary water. In the case of heavy water, the lack of experimental data in the critical region makes it impossible to establish a similar equation for the critical enhancement.

Equation (6) is certainly valid in the range $T = 277$ K (melting point) to $T = 775$ K for pressures up to 100 MPa, with the exclusion of the small area contained within

$$0.995 < T_r < 1.005 \quad \text{and} \quad 0.9 < \rho_r < 1.1,$$

as stipulated in the internationally agreed Representation. Beyond that, a comparison with measured values allows us to claim that extrapolation to 200 MPa within the same temperature limits is possible.

The uncertainties in the representation are illustrated graphically in Fig. 3; they range from a low of $\pm 1\%$ to a high of $\pm 5\%$.

The equation may probably be extrapolated with somewhat reduced reliability, to higher pressures and tempera-

tures (up to 1000 K) as an inspection of its graphical image beyond the above range does not show obvious nonphysical behavior.

4.3. Discussion

For liquid at atmospheric pressure, the agreement of Eq. (6) with the selected data is satisfactory as shown in Fig. 4. The data of Agayev *et al.* (1968)[V14,V15,V17] are slightly higher than the other data and the difference increases near the melting point. The deviations of the data other than those selected for the correlation are displayed in Fig. 5.

In the case of the liquid at high pressures, the deviations of the experimental data from Eq. (6) are shown along selected isotherms in Figs. 6–10, as functions of pressure. The deviations of the selected and other data are shown as functions of temperature in Figs. 11 and 12, respectively. The agreement of the data with the present correlation is satisfactory. In the regions above about 100 MPa and in the region near the critical point, the deviations become larger but they do not exceed the experimental uncertainty.

At pressures above about 100 MPa, only the data of Agayev *et al.*[V14-V18] and of Lee and Jonas (1972)[V21] are available. The measurements of Lee were, as mentioned before, not intended to produce usable viscosity values. When corre-
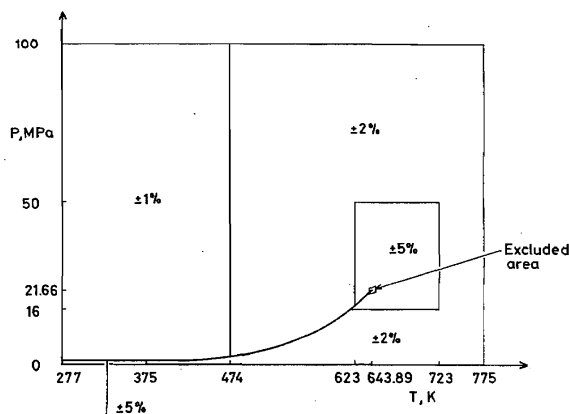
FIGURE 3. Uncertainties in the representation of viscosity.
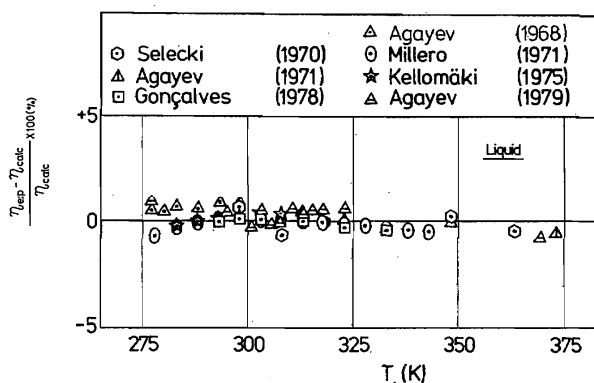
FIGURE 4. Deviation plot: viscosity (selected data, liquid, 1 atm).
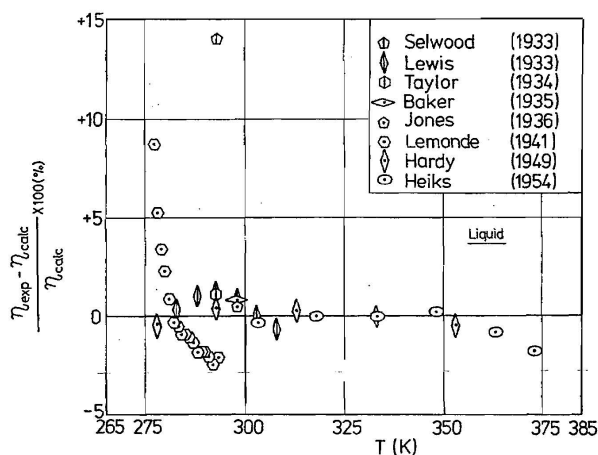
FIGURE 5. Deviation plot: viscosity (remaining data, liquid, 1 atm).
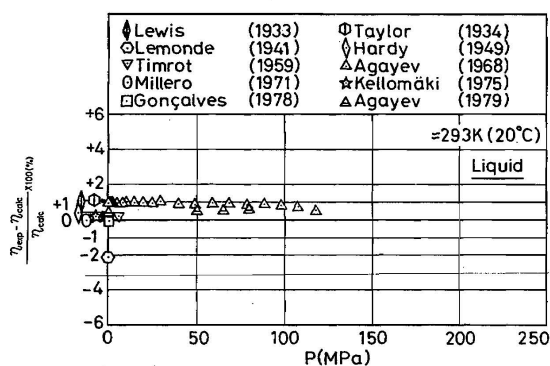
FIGURE 6. Deviation plot: viscosity (all data at 293 K, liquid).
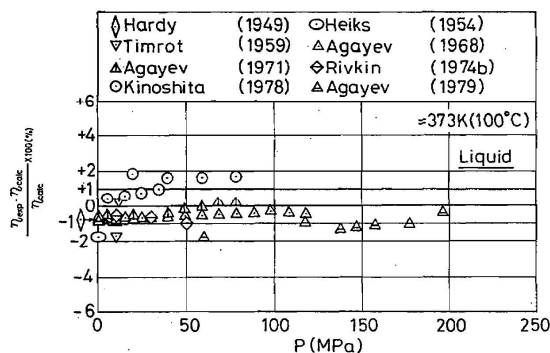
FIGURE 7. Deviation plot: viscosity (all data at 373 K, liquid).
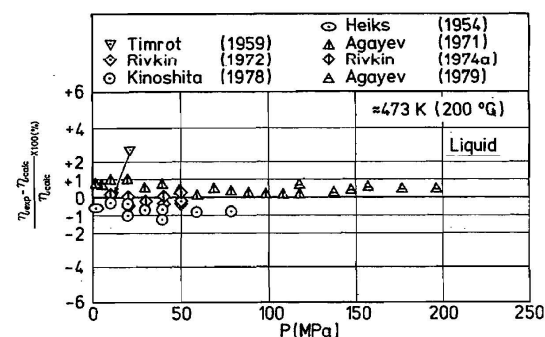
FIGURE 8. Deviation plot: viscosity (all data at 473 K, liquid).
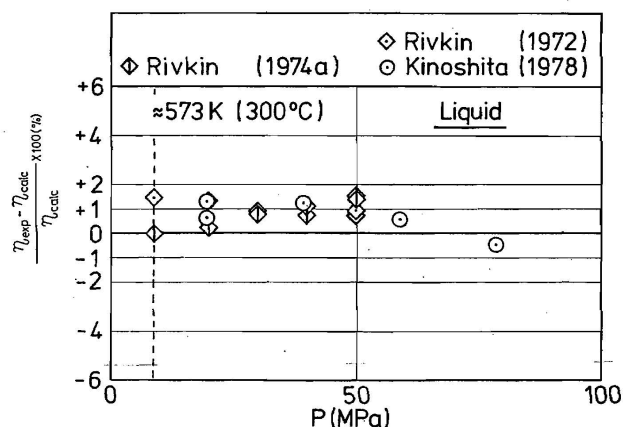
FIGURE 9. Deviation plot: viscosity (all data at 573 K, liquid).
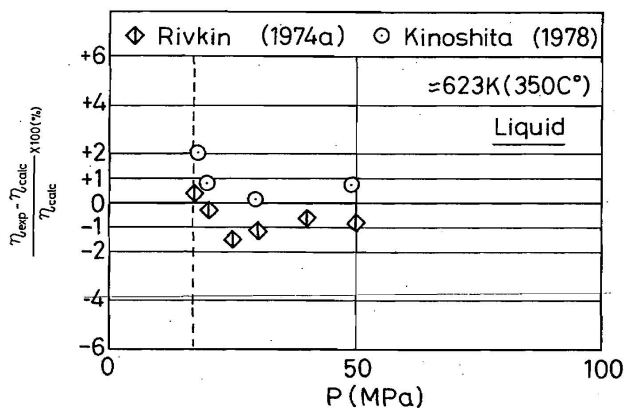
FIGURE 10. Deviation plot: viscosity (all data at 623 K, liquid).
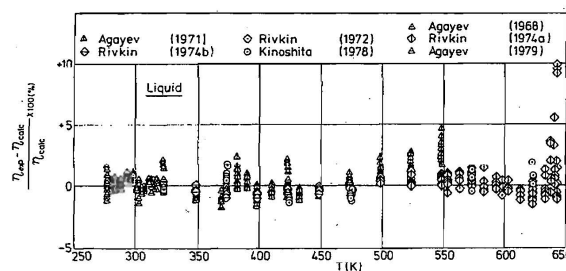
FIGURE 11. Deviation plot: viscosity (selected data, liquid, high pressure).
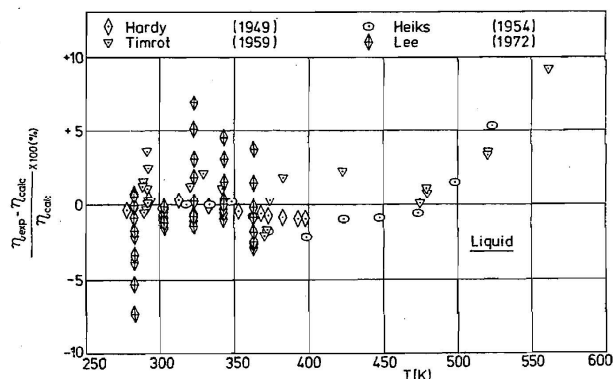
FIGURE 12. Deviation plot: viscosity (remaining data, liquid, high pressure).
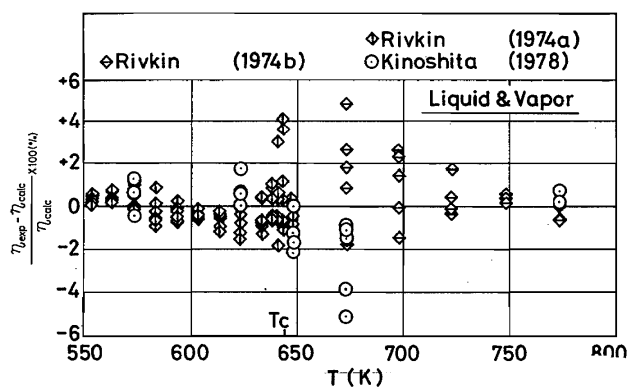
FIGURE 13. Deviation of experimental viscosity recalculated with densities from Hill's equation of state (Ref. E5).
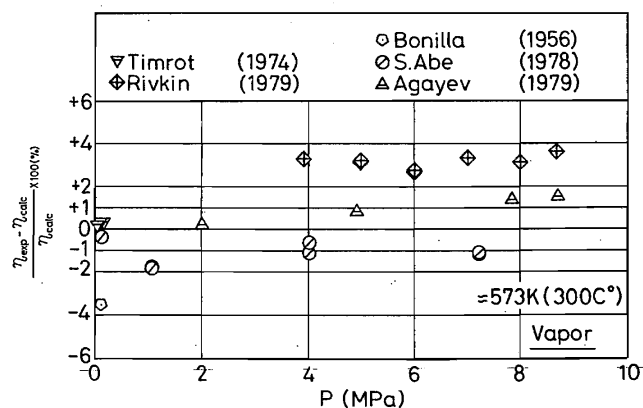
FIGURE 17. Deviation plot: viscosity (all data at 573 K, vapor).
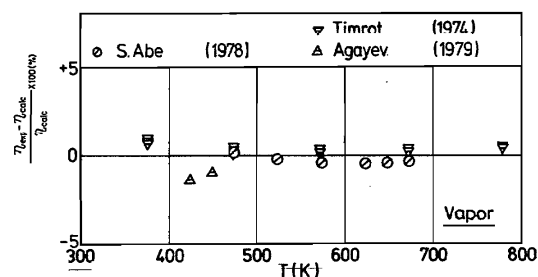
FIGURE 14. Deviation plot: viscosity (selected data, vapor, 1 atm).
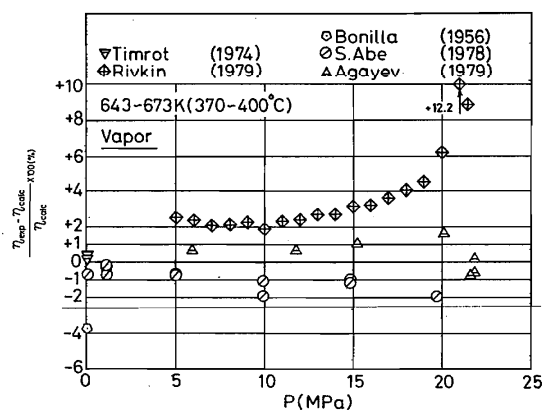
FIGURE 18. Deviation plot: viscosity (all data at 643–673 K, vapor).
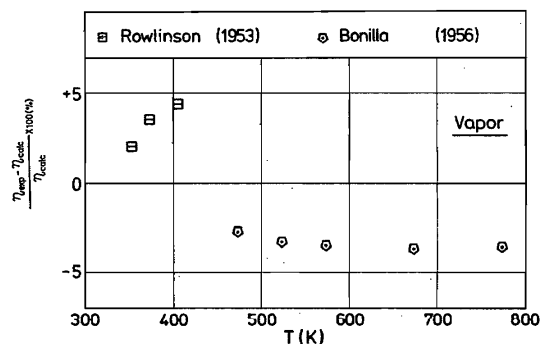
FIGURE 15. Deviation plot: viscosity (remaining data, vapor, 1 atm).
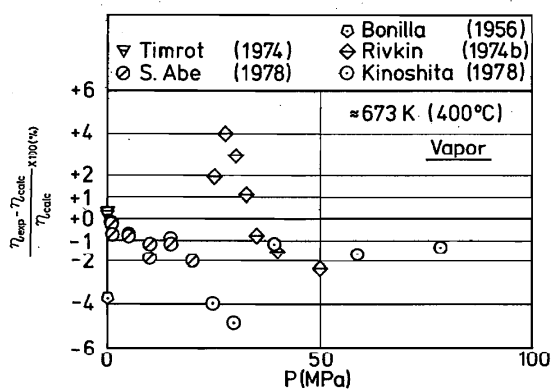
FIGURE 19. Deviation plot: viscosity (all data at 673 K, vapor).
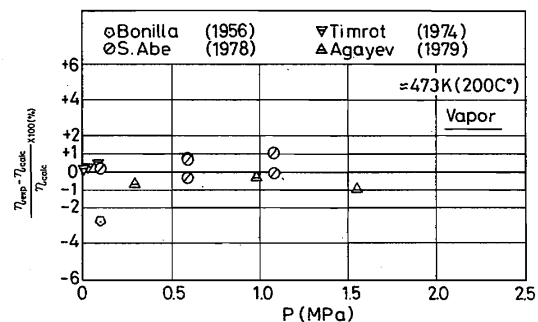
FIGURE 16. Deviation plot: viscosity (all data at 473 K, vapor).
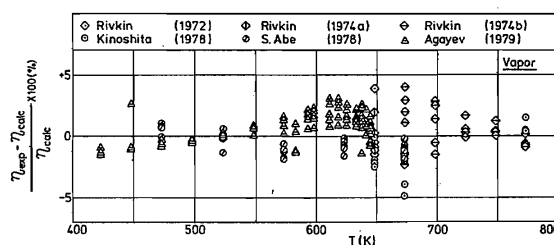
FIGURE 20. Deviation plot: viscosity (selected data, vapor, high pressure).
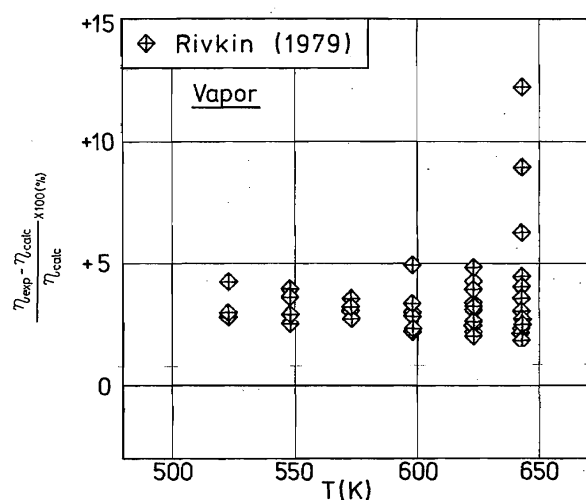
FIGURE 21. Deviation plot: viscosity (remaining data, vapor, high pressure).

lating the present equation, it was found that the data of Agayev[V14–V18] showed slightly larger deviations at pressures above about 100 MPa and this was partly attributed to the density used by Agayev who employed the equation of state of Kirillin.[1] That equation of state is valid only at pressures below 49 MPa (500 kgf/cm^2) and judging from a comparison with the equation of Hill,[E3–E5] the extrapolation to higher pressures is questionable. Nevertheless, the data of Agayev at pressures up to about 200 MPa have been displayed in the deviation plot.

Though the deviations near the critical point are large, we think that this departure may be partly due to the difference in the sources for density. As shown in Fig. 13, the recalculation of the experimental data considerably reduces the discrepancy. Here we used the density values from the equation of state of Hill et al.[E3–E5] Another possible reason for the larger deviations is the presence of the critical enhancement although its magnitude is not as large as for the thermal conductivity. The volume of experimental data in the near-critical region is inadequate to resolve this issue which must be left for a future study.

For vapor at atmospheric pressure, the agreement

between Eq. (6) and the selected data is quite satisfactory as shown in Fig. 14. Figure 15 depicts the deviations of the other data from the equation. The data of Rowlinson (1953)[V9] are higher and those of Bonilla et al. (1956)[V11] are lower than the present equation would suggest.

For vapor at high pressures, the deviations of the experimental data from our correlation equation are plotted along selected isotherms in Figs. 16–19, as functions of pressure. The deviations of the selected and other data are shown as functions of temperature in Figs. 20 and 21, respectively.

At subcritical temperatures, the present equation satisfactorily reproduces the pressure effect, negative as well as positive, of the data obtained by S. Abe et al. (1978)[V30] and by Agayev (1979).[V18] The data of Rivkin et al. (1979)[V27] are higher than the other two sets of data.

At 673 K (400 °C) and at pressures below 40 MPa, there is a disagreement between the data of Rivkin et al. (1974b)[V24–V26] and of Kinoshita et al. (1978).[V28,V29] The present equation seems to constitute a good compromise. At supercritical temperatures, other than 673 K, the present equation reproduces the available data fairly well.

5. Thermal Conductivity

5.1. Available Data

Experimental data of thermal conductivity are contained in Refs. T1–T9.

a. General Explanation

The measurement of the thermal conductivity of heavy water started after 1945. The experimental studies of the thermal conductivity of heavy water are listed in Tables 5–8 in chronological order. Various methods were employed to perform these measurements: a majority of investigators used steady-state methods, based on concentric cylinders, parallel plates, and a hot wire. The transient hot-wire method was employed in one study.

As shown in Fig. 22, in 1963 when Ref. 1 was published, only a limited set of data was available: they were for the liquid at atmospheric pressure and along the saturation line and only one set of data referred to the vapor. Figure 23 displays the ranges covered by the data published after 1963.

Table 5. Measurements of the thermal conductivity of heavy water
(liquid, atmospheric pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Bonilla,C.F.	1951	Liq.	Parallel plate	288.15 - 333.15	0.1(atmospheric)		T1
Meyer,F.	1953	Liq.	Column	290.75 - 329.35	0.1(atmospheric)	95	T2
Challoner,A.R.	1956	Liq.	Parallel plate	275.05 - 355.15	0.1(atmospheric)	99.95	T3
Vargaftik,N.B.	1959	Liq.	Hot-wire(steady)	298.45 - 628.35	20.4	99.9	T4,T5,T8
Klassen,T.V.	1959	Liq.	Hot-wire(steady)	300.85 - 346.45	0.1(atmospheric)	99.5	T12
Le Neindre,B.	1965	Liq.	Concentric-cylinder	313.15-crit.temp.	90.0	99.75	T16
Le Neindre,B.*	1968,1976	Liq.	Concentric-cylinder	315.75 - 643.05	100.1	99.75	T17,T19
Amirkhanov,Kh.I.	1974	Liq.	Parallel plate	298.15 - 623.15	245.3	99.75	T23,T24
Bibik,A.P.	1975	Liq.	Hot-wire(transient)	273.15 - 313.15	0.1(atmospheric)	99.8	T26
Rastorguyev,Yu.L.	1975	Liq.	Concentric-cylinder	262.51 - 487.35	217.7	99.8	T27,T28
Yata,J.*	1979	Liq.&Vap	Concentric-cylinder	327.85 - 773.25	150.0	99.8	T29

Table 6.   Measurements of the thermal conductivity of heavy water
(liquid, high pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Vargaftik,N.B.	1959	Liq.	Hot-wire(steady)	298.45 - 628.35	20.4	99.9	T4,T5,T8
Ziebland,H.	1960	Liq.	Concentric-cylinder	348.85 - 532.95	29.8	99.85	T13,T14
Le Neindre,B.	1965	Liq.	Concentric-cylinder	313.15-crit.temp.	90.0	99.75	T16
Le Neindre,B.*	1968,1976	Liq.	Concentric-cylinder	315.75 - 643.05	100.1	99.75	T17,T19
Amirkhanov,Kh.I.	1974	Liq.	Parallel plate	298.15 - 623.15	245.3	99.75	T23,T24
Rastorguev,Yu.L.	1975	Liq.	Concentric-cylinder	262.51 - 487.35	217.7	99.8	T27,T28
Yata,J.*	1979	Liq.&Vap.	Concentric-cylinder	327.85 - 773.25	150.0	99.8	T29

Table 7.   Measurements of the thermal conductivity of heavy water
(vapor, atmospheric pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Vargeftik,N.B.	1962	Vap.	Hot-wire(steady)	417.75 - 777.25	24.5	99.9	T6,T8
Vargaftik,N.B.	1963	Vap.	Hot-wire(steady)	380.11 - 775.09	0.1(atmospheric)		T7,T8
Baker,C.E.	1964	Vap.	Hot-wire(steady)	381.2 - 525.6	0.1(atmospheric)		T15
Bury,P.*	1068	Vap.	Concentric-cylinder	383.15 - 603.15	12.5		T18
Dijkema,K.M.	1972	Vap.	Concentric-cylinder &thermistor bridge	333	0.018(saturation)		T20
Vargaftik,N.B.*	1973	Vap.	Hot-wire(steady)	400.70 -1042.85	< 0.1	99.8	T9
Vargaftik,N.B.	1975	Vap.	Hot-wire(AC)	525.4 - 909.3	0.2		T10,T11
Amirkhanov,Kh.I.	1978	Vap.	Parallel-plate	648.95 - 874.95	250	99.75	T25

Table 8 .   Measurements of the thermal conductivity of heavy water
(vapor, high pressure)

First author	Year	State	Method	Temperature range (K)	Maximum pressure (MPa)	Purity(%)	Ref.no.
Vargaftik,N.B.	1962	Vap.	Hot-wire(steady)	417.75 - 777.25	24.5	99.9	T6,T8
Bury,P.*	1968	Vap.	Concentric-cylinder	383.15 - 603.15	12.5		T18
Tarzimanov,A.A.*	1974	Vap.	Concentric-cylinder	502.15 - 822.65	80.0	99.7	T21,T22
Amirkhanov,Kh.I.	1978	Vap.	Parallel-plate	648.95 - 874.95	250	99.75	T25
Yata,J.	1979	Liq.&Vap.	Concentric-cylinder	327.85 - 773.25	150.0	99.8	T29

The region extends over a very wide range of temperatures and pressures, namely, from the melting curve to 873 K (600 °C) and up to 250 MPa in pressure. This is wider than that covered by viscosity. In contrast with viscosity, the data for thermal conductivity are available in every sub-region. The thermal conductivity of heavy water exhibits, just as that of other substances, a much stronger critical enhancement than does the viscosity. Although this enhancement was studied to some extent by Tarzimanov and Zainullin (1974),[T21,T22] not enough experimental evidence is available to perform a complete correlation of the critical thermal conductivity enhancement.

b. Liquid Phase

Eleven sets of data are available for the liquid at atmospheric pressure, as shown in Table 5. Among these data,

those of Klassen (1959)[T12] and of Bibik, Litvinenko, and Radchenko (1975)[T26] seem to be questionable. Klassen measured the thermal conductivity of heavy water using an apparatus of the steady-state hot-wire variety which was similar to that employed by Vargaftik, Oleshuk, and Belyakova.[T4,T5,T8] The results are too high compared to other experimental data at the highest temperatures and the occurrence of convection is suspected.

Bibik, Litvinenko, and Radchenko[T26] measured the ratio of the thermal conductivities of heavy and ordinary water by means of a transient hot-wire apparatus. Though the result is given as a cubic function of temperature, it appears unreasonable. We suspect that the numerical constants quoted in the paper for the equation contain printing errors.

Thus we consider in practice of eight sets of data. The degree of consistency among these data is inferior compared to that of viscosity data in the same region in spite of the fact
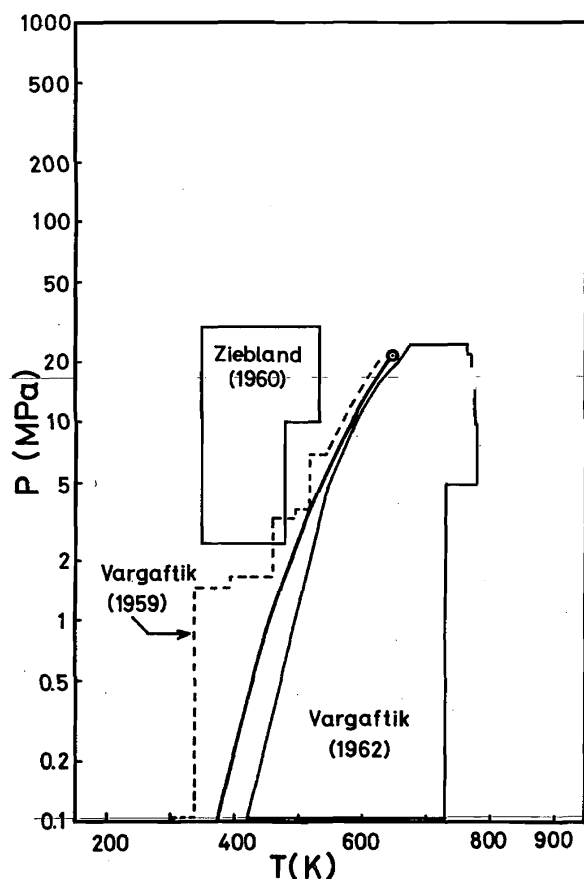
FIGURE 22. Experimental studies of thermal conductivity of D_2O (prior to 1963).
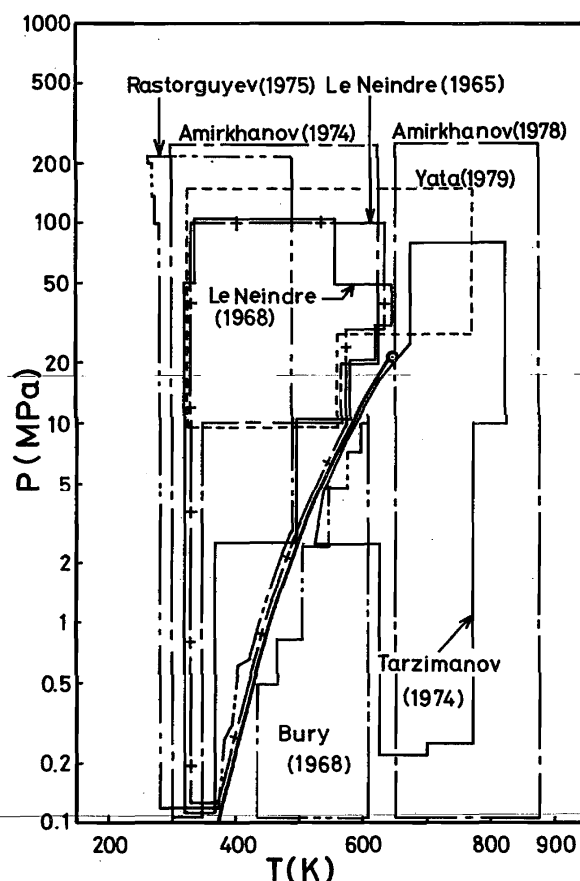
FIGURE 23. Experimental studies of thermal conductivity of D_2O (after 1963).

that the increase in magnitude of experimental uncertainties for thermal conductivities has been taken into account.

Fortunately, some researchers measured both ordinary and heavy water and the ratio of the thermal conductivities of the two substances can be determined from their results. The ratios thus obtained agree well with each other, except for that calculated from the paper by Rastorguyev, Grigoryev, and Ishkhanov (1975).[T27,T28] Examining the latest thermal conductivity data for ordinary water in this region and the thermal conductivity ratio mentioned before, it is possible to conclude which values are most probable. This leads us to the conclusion that the data of Le Neindre (1968)[T17,T19] are most reliable. At temperatures below about 313 K (40 °C), where Le Neindre's data are not available, the temperature dependence of Rastorguyev's data[T27,T28] seems reasonable at atmospheric pressure, though the absolute values are considered slightly too high.

As shown in Table 6, seven sets of data are available for the liquid at high pressures. Among them, the data by Amirkhanov, Adamov, and Magomedov (1974)[T23,T24] call for a detailed discussion. Amirkhanov and co-workers measured the thermal conductivity of heavy water up to about 250 MPa, using a parallel-plate apparatus. At lower pressures the results agree fairly well with the data of Le Neindre, Bury, Tufeu, Johannin, and Vodar (1968),[T17,T19] which, as mentioned before, we consider to be most reliable,

but at higher pressures and at temperatures above 348 K (75 °C), the pressure dependence of Amirkhanov's results becomes much stronger than that of other authors. A similar tendency was observed in the case of ordinary water.

With Amirkhanov's data excluded, the consistency among the remaining data seems to be fair up to about 473 K (200 °C), but the data of Rastorguyev, Grigoryev, and Ishkhanov[T27,T28] appear to be slightly higher systematically. The ratio of the thermal conductivities of heavy and ordinary water calculated from their data at high pressures does not agree with the values obtained from the data of other authors.

At temperatures above 473 K (200 °C), the agreement deteriorates further. In the liquid region, no researchers applied corrections for radiative heat loss. But, at high temperatures, the effect of radiative heat loss is certainly significant. The magnitude of this effect depends strongly on the design and dimensions of the apparatus. Therefore, we believe that a portion of the discrepancy observed at temperatures above 473 K (200 °C) is due to inadequate corrections for radiative heat loss.

c. Gaseous Phase

Eight sets of data are available for the vapor at atmospheric pressure, as shown in Table 7. The consistency among these data is comparatively poor. The ratios of the

thermal conductivities of heavy and ordinary water vapor were calculated for each author's data. The ratios thus obtained agreed very well among different authors. Using these ratios and combining them with the relatively abundant data for steam (ordinary water vapor) in the same range, it becomes possible to deduce probable values for the thermal conductivity of heavy water vapor at atmospheric pressure. By these means we concluded that the data of Bury, Le Neindre, Tufeu, Johannin, and Vodar (1968)[T18] and of Vargaftik, Vanicheva, and Yakush (1973)[T9] should be given preference in the correlation.

Five sets of data, Table 8, are available for the vapor at high pressures. Vargaftik and Oleshuk (1962)[T6,T8] measured the pressure dependence of the thermal conductivity of heavy water vapor in a very wide range of temperatures using the steady-state hot-wire method previously employed for the measurement on the saturated liquid of heavy water. Bury, Le Neindre, Tufeu, Johannin, and Vodar (1968)[T18] studied the pressure dependence of the thermal conductivity of heavy water vapor at subcritical temperatures by means of an apparatus of the concentric-cylinder type. Tarzimanov and Zainullin (1968)[T21,T22] measured the thermal conductivity of heavy water vapor in very wide ranges of temperatures and pressures, including the vicinity of the saturation line and the critical point using an apparatus of the concentric-cylinder type. Amirkhanov, Adamov, and Magomedov (1978)[T25] studied the thermal conductivity of heavy water vapor using the parallel-plate apparatus which they also employed for the measurement on liquid heavy water. Yata, Minamiyama, Kim, Yokogawa, and Murai (1979)[T29] obtained the thermal conductivity of heavy water both in the liquid and dense-gas region by means of a concentric-cylinder apparatus.

Corrections for radiative heat loss were applied by all authors except for Bury and co-workers[T18] and Yata and co-workers.[T29]

The consistency among these data is poor and certainly worse than for ordinary water vapor. For instance, the data of Yata and co-workers[T29] are systematically higher than those of Tarzimanov and Zainullin,[T21,T22] in spite of the fair agreement observed in the data for light water vapor obtained by the same authors. This may be partly due to insufficient information concerning the optical properties of heavy water vapor which are required when correcting for radiative heat loss.

Among these data, those of Bury and co-workers[T18] and of Tarzimanov and Zainullin[T21,T22] agree fairly well with each other and with the most probable data at atmospheric pressure mentioned before. The data of Vargaftik and Oleshuk[T6,T8] also show fair agreement with these two sets of data at temperatures below about 673 K (400 °C).

d. Critical Region

There exists only one set of data in the near-critical region. This is the set produced by Tarzimanov and Zainullin (1974).[T21,T22] The data confirm the existence of the critical enhancement of thermal conductivity and display a behavior similar to that observed in ordinary water.

5.2. Equation for the Thermal Conductivity of Heavy Water

a. Preliminary Considerations

The single existing formulation for the thermal conductivity of heavy water was that published earlier by the present authors.[2-4] Though the equation was revised once to adjust to the density values taken from the first version of Hill's equation of state,[E1,E2] the pseudocritical constants incorporated as reference values were different from those used in the equation of state.

For this reason, a new correlation was undertaken. The present reference values are identical with those adapted in the latest version of Hill's equation.[E3-E5]

When correlating an equation for the thermal conductivity, it must be borne in mind that the critical enhancement cannot be adequately represented if the ratio $\lambda(T, \rho)/\lambda_0(T)$ is used. Here, $\lambda_0(T)$ is the thermal conductivity of the vapor at a sufficiently low density. For this reason, the present correlation introduces the excess thermal conductivity $\lambda(T, \rho) - \lambda_0(T)$ and expresses it as a function of temperature and density. The earlier equation for the thermal conductivity of heavy water had a similar form.

The reference constants and the density were the same as those described in Sec. 4.2.b.

b. Selected Experimental Data

After a critical evaluation, we selected the following sets of data to serve as a basis for the final correlation. These are distinguished by asterisks in Tables 5–8.

Liquid region:
Le Neindre and co-workers[T17,T19]
Yata and co-workers[T29]

Vapor region:
Bury and co-workers[T18]
Vargaftik, Vanicheva, and Yakush[T9]
Tarzimanov and Zainullin[T21,T22]

c. Correlated Equation of the Thermal Conductivity

The resulting equation is as follows:

$$\lambda = A\left[\lambda_0 + \Delta\lambda + \Delta\lambda_c + \Delta\lambda_L\right], \tag{7}$$

where

$$\lambda_0 = \sum_{i=0}^{5} A_i T_r^{\,i}, \tag{7a}$$

$$\Delta\lambda = B_0\left[1 - \exp(B_e\rho_r)\right] + \sum_{j=1}^{4} B_j\rho_r^{\,j}, \tag{7b}$$

$$\Delta\lambda_c = C_1 f_1(T_r) f_2(\rho_r)\left(1 + [f_2(\rho_r)]^2\left\{\frac{C_2[f_1(T_r)]^4}{f_3(T_r)} + \frac{3.5 f_2(\rho_r)}{f_4(T_r)}\right\}\right), \tag{7c}$$

$$\Delta\lambda_L = D_1[f_1(T_r)]^{1.2}\left\{1 - \exp\left[-\left(\frac{\rho_r}{2.5}\right)^{10}\right]\right\}, \tag{7d}$$

and

$$f_1(T_r) = \exp(C_{T1} T_r + C_{T2} T_r^{\,2}), \tag{7e}$$

$$f_2(\rho_r) = \exp[C_{R1}(\rho_r - 1)^2] + C_{R2}\exp[C_{R3}(\rho_r - \rho_{r1})^2], \tag{7f}$$

$$f_3(T_r) = 1 + \exp[60(\tau - 1) + 20], \quad (7g)$$

$$f_4(T_r) = 1 + \exp[100(\tau - 1) + 15], \quad (7h)$$

$$\tau = \frac{T_r}{|T_r - 1.1| + 1.1}. \quad (7i)$$

The reduced variables are

$$T_r = T/T_c \quad \text{and} \quad \rho_r = \rho/\rho_c, \quad (7j)$$

and the meaning of the symbols is as follows:

λ—thermal conductivity T_c—pseudocritical temperature
T—temperature ρ_c—pseudocritical density
ρ—density

The constants appearing in Eqs. (7)–(7j) are listed below.

$$T_c = 643.89 \text{ K}$$

$$\rho_c = 358 \text{ kg/m}^3$$

$$A = 0.7421\,28 \times 10^{-3} \text{ W/(m·K)}$$

A_0	=	1.0000 0	C_1	=	0.3542 96×10⁵
A_1	=	37.3223	C_2	=	0.5000 00×10¹⁰
A_2	=	22.5485			
A_3	=	13.0465	C_{T1}	=	0.1448 47
A_4	=	0.0	C_{T2}	=	− 5.6449 3
A_5	=	− 2.6073 5	C_{R1}	=	− 2.8000 0
			C_{R2}	=	− 0.0807 3854 3
B_e	=	− 2.5060 0	C_{T3}	=	− 17.9430
B_0	=	− 167.310	ρ_{r1}	=	0.1256 98
B_1	=	483.656			
B_2	=	− 191.039	D_1	=	− 741.112
B_3	=	73.0358			
B_4	=	− 7.5746 7			

The various terms in Eq. (7) have the following significance:

λ_0: Thermal conductivity at zero density

$\Delta\lambda$: Excess thermal conductivity without the critical enhancement

$\Delta\lambda_c$: Critical enhancement or steep increase of the thermal conductivity of subcritical vapor

$\Delta\lambda_r$: Decrease of the thermal conductivity of low temperature liquid with decreasing temperature

The form of Eq. (7) is empirical. Although the critical enhancement of the available experimental data is fully taken into account, Eq. (7) gives a finite value at the critical point, which is in conflict with the theory. For this reason, we must exclude a very narrow region near the critical point itself.

As was the case with viscosity, the present equation for thermal conductivity is certainly valid at pressures below 100 MPa. An examination of deviation plots suggests that it is valid in the temperature range from $T = 277$ K (melting point) to $T = 825$ K, except for a region contained within

$$0.99 < T_r < 1.05,$$

and

$$0.8 < \rho_r < 1.2.$$

A comparison of the equation with the experimental data at higher pressures permits us to claim that its validity can be extended to 250 MPa at the cost of stipulating a larger uncertainty.
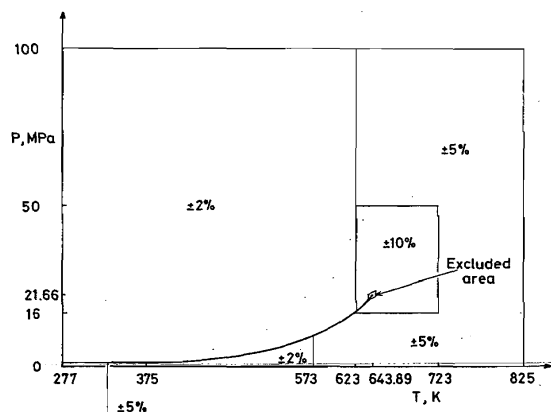
FIGURE 24. Uncertainties in the representation of thermal conductivity.

The uncertainties in the thermal conductivity range from a low of $\pm 2\%$ to a high of $\pm 10\%$; they are represented graphically in Fig. 24.

5.3. Discussion

Figures 25 and 26 display the deviations of experimental data for the liquid at atmospheric pressure from Eq. (7). Agreement with the data of Le Neindre et al. (1968)[T17,T19] as well as with the remaining data, except perhaps Klassen,[T12] is satisfactory, even though the fit in this region employed only Le Neindre's data.

Deviations along selected isotherms for the liquid under high pressure, are shown in Figs. 27–31. Below 313 K (40 °C), where Le Neindre and co-workers (1968)[T17,T19] gave no data, departures from Rastorguyev (1975)[T27,T28] reach about 1%. All of the selected data under high pressure are seen plotted against temperature in Fig. 32. Agreement is excellent below 500 K. As the critical temperature is approached, we observe a trend towards systematically larger departures.

Figure 33 illustrates the compromise achieved by the present authors with their correlation. The diagram uses density as the independent argument and clearly demonstrates that the data for the gas place themselves systematically below the correlation surface, whereas those for the
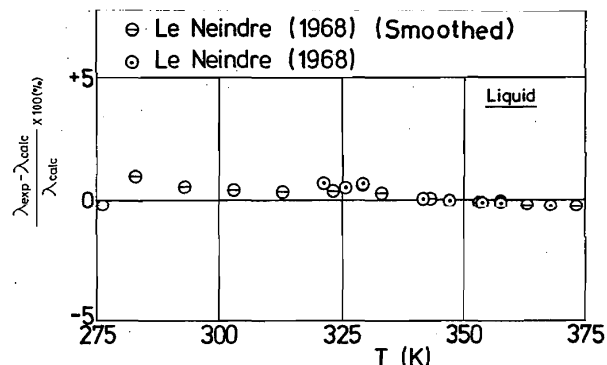
FIGURE 25. Deviation plot: thermal conductivity (selected data, liquid, 1 atm).
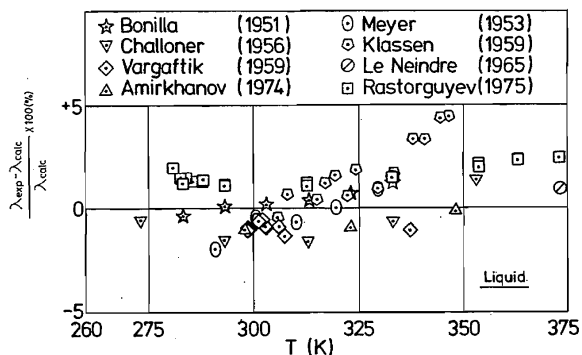
FIGURE 26. Deviation plot: thermal conductivity (remaining data, liquid, 1 atm).
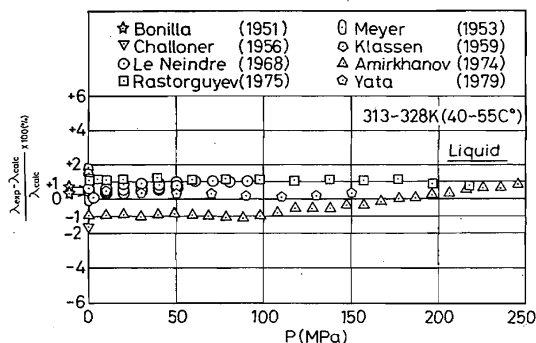
FIGURE 27. Deviation plot: thermal conductivity (all data at 313 K, liquid).
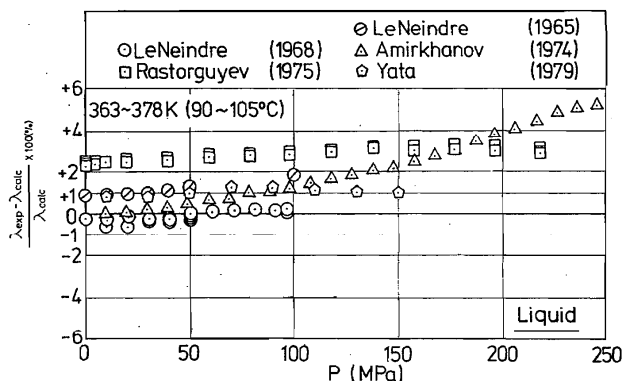
FIGURE 28. Deviation plot: thermal conductivity (all data at 363–378 K, liquid).
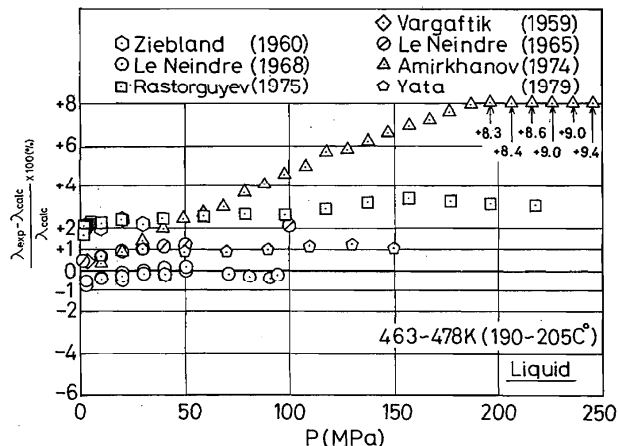
FIGURE 29. Deviation plot: thermal conductivity (all data at 463–478 K, liquid).
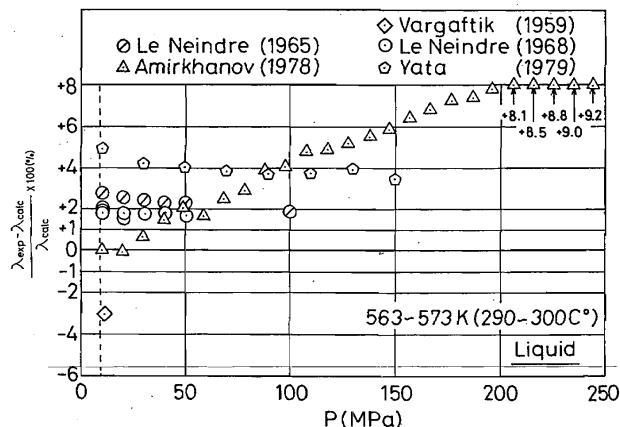
FIGURE 30. Deviation plot: thermal conductivity (all data at 563–573 K, liquid).
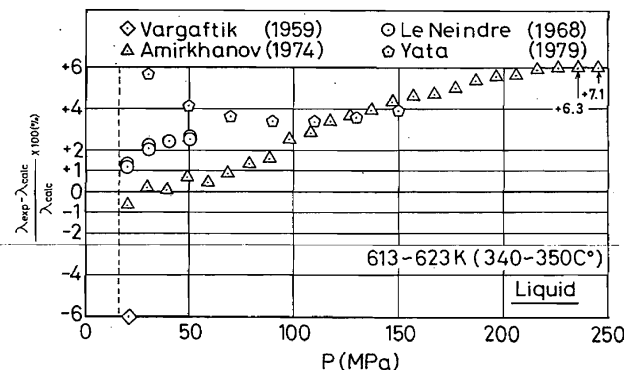
FIGURE 31. Deviation plot: thermal conductivity (all data at 613–623 K. liquid).
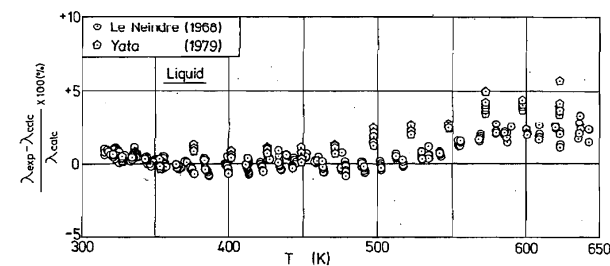
FIGURE 32. Deviation plot: thermal conductivity (selected data, liquid, high pressure).
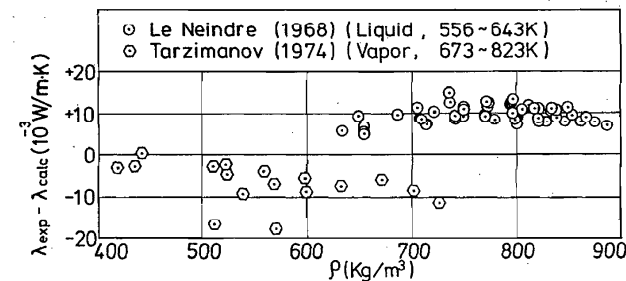
FIGURE 33. Deviation plot: thermal conductivity (critical region, liquid and vapor).
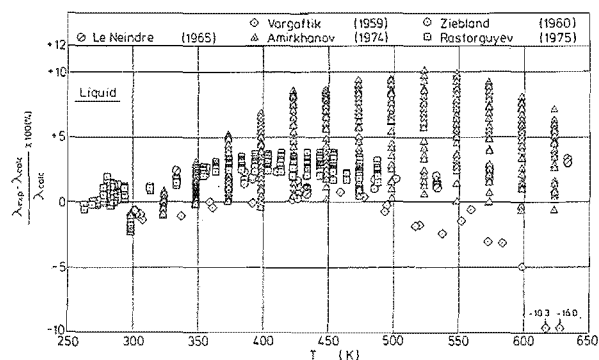
FIGURE 34. Deviation plot: thermal conductivity (remaining data, liquid, high pressure).
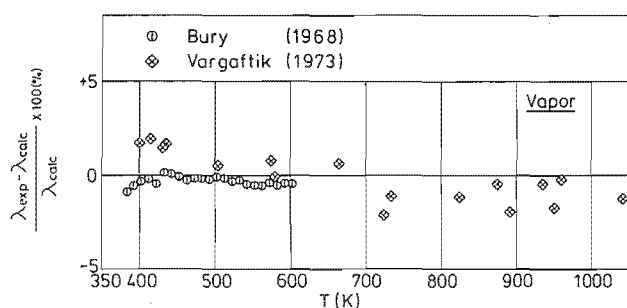
FIGURE 35. Deviation plot: thermal conductivity (selected data, vapor, 1 atm).
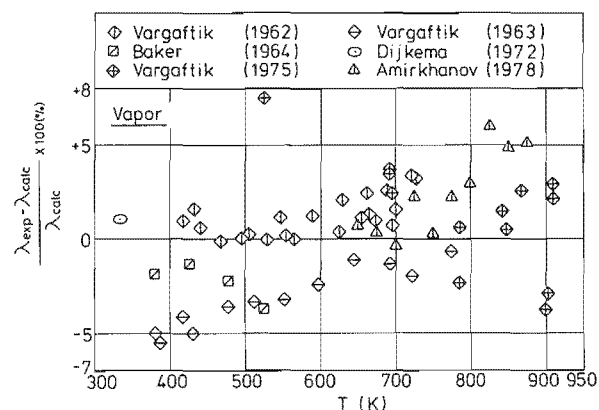
FIGURE 36. Deviation plot: thermal conductivity (remaining data, vapor, 1 atm).
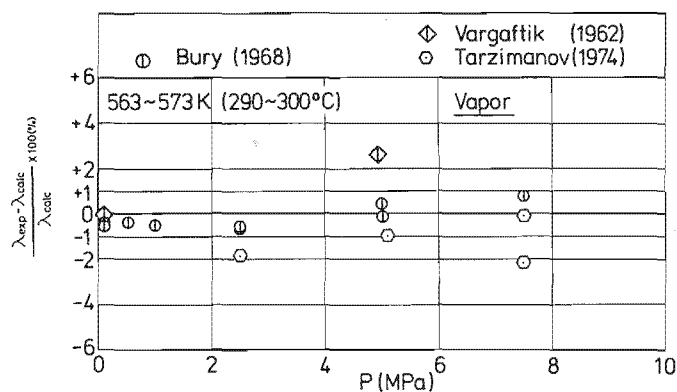
FIGURE 37. Deviation plot: thermal conductivity (all data at 563–573 K, vapor).
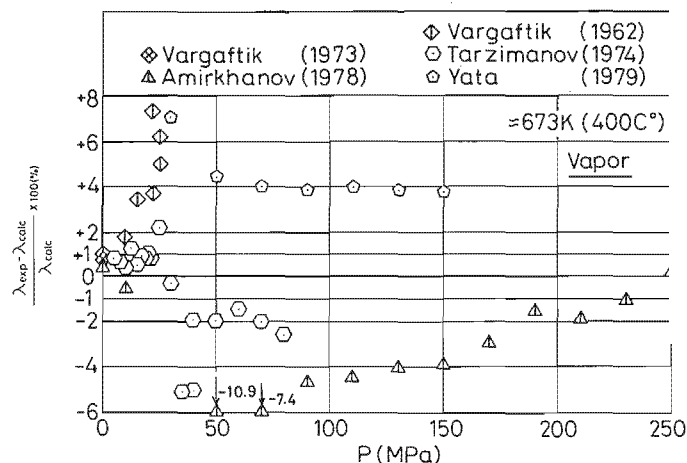
FIGURE 38. Deviation plot: thermal conductivity (all data at 673 K, vapor).
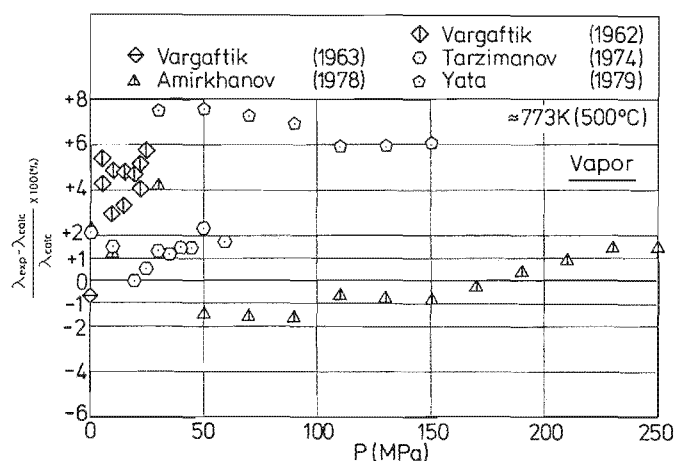
FIGURE 39. Deviation plot: thermal conductivity (all data at 773 K, vapor).
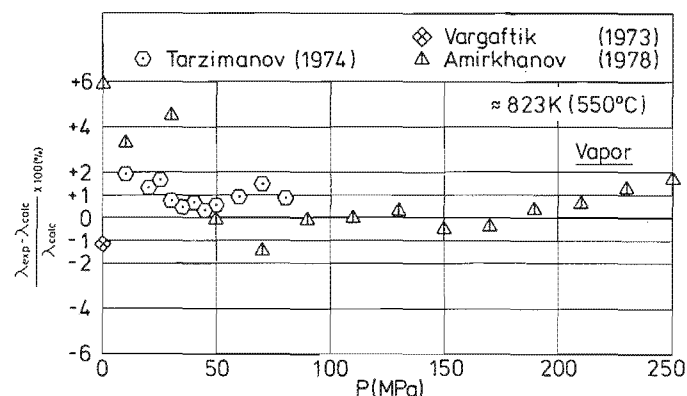
FIGURE 40. Deviation plot: thermal conductivity (all data at 823 K, vapor).

liquid congregate systematically above it, both overlappng somewhat across the critical density. We can conclude that the experimental uncertainty in this region is large and we fit Eq. (7) to strike a compromise. We further took into account that Le Neindre et al. (1968)[T17,T19] as well as Yata et al. (1979)[T29] did not apply a radiation correction to the data in the liquid phase in this temperature range. Comparisons with other experimental data are shown in Fig. 34.

Figure 35 shows deviations for the vapor at atmospheric pressure in the data of Bury (1968)[T18] and Vargaftik et al.
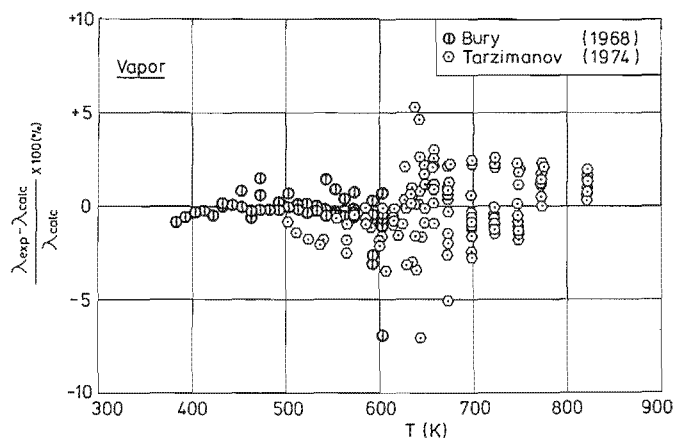
FIGURE 41. Deviation plot: thermal conductivity (selected data, vapor, high pressure).
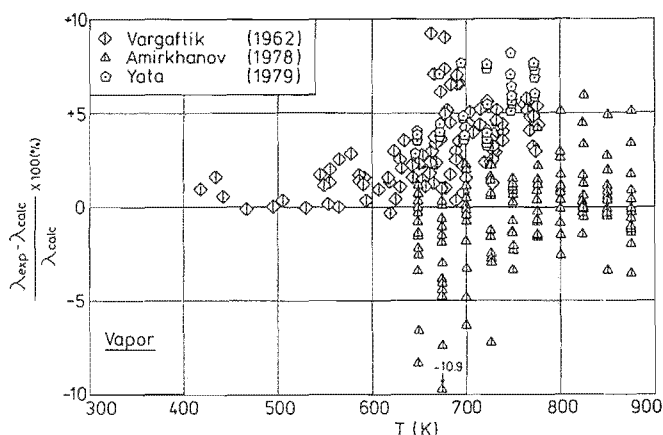
FIGURE 42. Deviation plot: thermal conductivity (remaining data, vapor, high pressure).
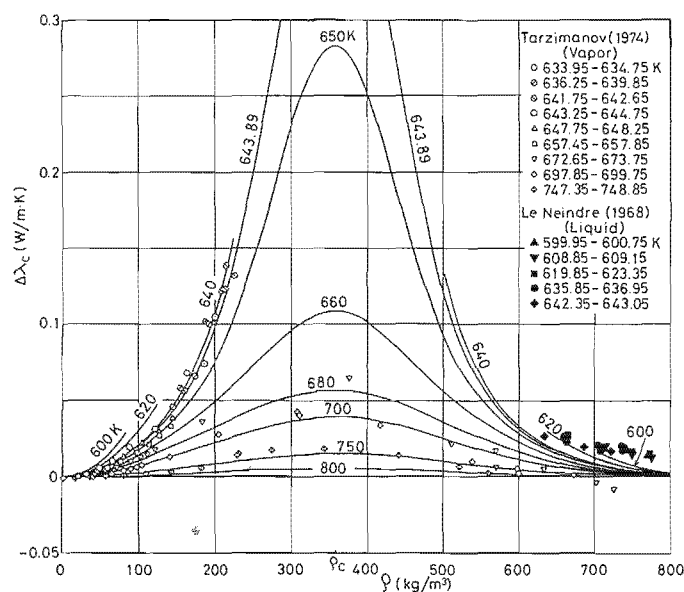
FIGURE 43. Critical enhancement of thermal conductivity.

(1973).[T9] Agreement is satisfactory given the experimental uncertainty. Deviations of other data are shown in Fig. 36. At high pressures, deviations of experimental data from Eq. (7) are shown along selected isotherms in Figs. 37–40. Selected data are plotted in Fig. 41 against temperature. Agree-

ment among the data is not as good as for viscosity, but Eq. (7) produces a reasonable compromise, particularly if we take into account the inherent difficulty of the measurement. Most of the data fall within a band of $\pm 3\%$ from Eq. (7). The deviations of the remaining data are shown in Fig. 42. Below 650 K, the deviations of Vargaftik's data (1962)[T6,T8] fall below 3%.

Although Eq. (7) does not incorporate the correct divergence of the thermal conductivity at the critical point, every effort was made to fit the equation to all currently available experimental points in the critical region. The result is shown in Fig. 43, which describes the critical enhancement of the thermal conductivity of D_2O. Agreement is satisfactory. The vapor data by Tarzimanov and Zainullin (1974)[T21,T22] in the right-hand corner of Fig. 43 fall lower while the liquid data of Le Neindre et al. (1968)[T17,T19] tend to place themselves higher than the correlation. This inconsistency between the two ends, that is between the gaseous and liquid phases corresponds to that pointed out in conjunction with Fig. 33.

6. Gaseous Diffusion Coefficient

Experimental data on the gaseous diffusion coefficient are extremely scarce. But experimental data are available[D1,D2] for the binary systems of D_2O-vapor with air, helium, methane, neon, nitrogen, carbon monoxide, oxygen, argon, or carbon dioxide. These data are listed in Table 9. For liquid state, a number of data for dilute solutions (small amount of other substance in liquid D_2O) is also available. Data of the self-diffusion coefficient could not be found in literatures.

7. Tables of Transport Properties of D_2O

A consistent set of tables of transport properties of D_2O in a range of temperature and pressure was calculated using

Table 9. Gaseous diffusion coefficient for binary systems with D_2O

Reference [D1]	Kimpton, D. D. and Wall, F. T. (1952) Method : evaporation tube		
System	$T(K)$	$T(^\circ C)$	D_{12} $(10^{-4} m^2/s)$ at 1 atm
D_2O - air	297.95	24.8	0.247
	313.15	40.0	0.277
	318.15	45.0	0.288
	333.15	60.0	0.314

Reference [D2]	Diikema, K. M., Stautkhart, Zh. S. and de Vriz, D. A. (1972) Method : evaporation tube		
System	$T(K)$	$T(^\circ C)$	D_{12} $(10^{-4} m^2/s)$ at 1 atm
D_2O - H_2	295.0	21.85	0.854
D_2O - He	295.0	21.85	0.804
D_2O - CH_4	295.0	21.85	0.247
D_2O - Ne	295.0	21.85	0.391
D_2O - N_2	295.0	21.85	0.243
D_2O - CO	295.0	21.85	0.232
D_2O - air	295.0	21.85	0.246
D_2O - O_2	295.0	21.85	0.251
D_2O - Ar	295.0	21.85	0.231
D_2O - CO_2	295.0	21.85	0.154

Table 10.   Viscosity of D_2O (10^{-6}Pa·s)

P(MPa) \ T(°C)	3.79	25.0	50.0	75.0	100.0	150.0	200.0	250.0	300.0
0.1	2088	1095	651.2	444.1	328.8	14.58	16.63	18.72	20.84
0.5	2086	1095	651.3	444.2	329.0	210.1	16.45	18.61	20.78
1.0	2085	1095	651.4	444.4	329.2	210.2	16.24	18.48	20.70
2.5	2080	1094	651.8	444.9	329.7	210.7	152.2	18.08	20.48
5.0	2072	1093	652.4	445.8	330.6	211.6	153.0	118.1	20.13
7.5	2065	1092	653.0	446.7	331.5	212.4	153.8	119.0	19.81
10.0	2058	1092	653.6	447.6	332.4	213.2	154.5	119.8	94.3
12.5	2051	1091	654.2	448.5	333.3	214.0	155.3	120.6	95.5
15.0	2044	1090	654.8	449.3	334.2	214.8	156.1	121.4	96.6
17.5	2037	1089	655.5	450.2	335.1	215.6	156.8	122.2	97.7
20.0	2031	1089	656.1	451.0	335.9	216.4	157.5	123.0	98.7
22.5	2025	1088	656.7	451.9	336.8	217.2	158.2	123.7	99.6
25.0	2019	1087	657.3	452.7	337.7	217.9	159.0	124.4	100.6
27.5	2013	1087	657.7	453.6	338.5	218.7	159.7	125.1	101.5
30.0	2007	1086	658.6	454.4	339.4	219.5	160.4	125.8	102.3
35.0	1997	1085	659.8	456.1	341.0	221.0	161.7	127.2	103.9
40.0	1987	1085	661.1	457.8	342.7	222.4	163.1	128.5	105.4
45.0	1978	1084	662.4	459.4	344.3	223.9	164.4	129.8	106.8
50.0	1969	1083	663.7	461.0	346.0	225.3	165.6	131.0	108.2
55.0	1962	1083	665.0	462.7	347.6	226.7	166.9	132.2	109.5
60.0	1955	1083	666.3	464.3	349.1	228.1	168.1	133.3	110.7
65.0	1948	1082	667.6	465.9	350.7	229.5	169.3	134.5	111.8
70.0	1943	1082	669.0	467.4	352.3	230.8	170.5	135.6	112.9
75.0	1938	1082	670.3	469.0	353.8	232.2	171.7	136.6	114.0
80.0	1934	1083	671.7	470.6	355.3	233.5	172.8	137.6	115.0
85.0	1930	1083	673.1	472.1	356.8	234.7	173.9	138.7	116.0
90.0	1927	1083	674.5	473.7	358.3	236.0	175.0	139.6	117.0
95.0	1925	1084	675.9	475.2	359.8	237.3	176.1	140.6	117.9
100.0	1923	1085	677.4	476.8	361.2	238.5	177.1	141.5	118.8

P(MPa) \ T(°C)	350.0	375.0	400.0	425.0	450.0	475.0	500.0
0.1	22.97	24.03	25.09	26.15	27.20	28.25	29.29
0.5	22.94	24.01	25.08	26.15	27.21	28.26	29.31
1.0	22.90	23.99	25.08	26.15	27.22	28.29	29.34
2.5	22.80	23.94	25.06	26.17	27.27	28.36	29.43
5.0	22.66	23.87	25.06	26.22	27.37	28.49	29.60
7.5	22.56	23.85	25.09	26.31	27.49	28.65	29.78
10.0	22.52	23.87	25.17	26.43	27.65	28.83	29.99
12.5	22.60	23.98	25.31	26.59	27.84	29.05	30.22
15.0	22.92	24.21	25.53	26.82	28.08	29.30	30.49
17.5	70.2	24.7	25.9	27.1	28.38	29.60	30.78
20.0	73.6	25.7	26.4	27.5	28.75	29.94	31.12
22.5	76.1	31.9	27.3	28.1	29.21	30.36	31.51
25.0	78.2	58.9	29.0	29.0	29.81	30.85	31.95
27.5	80.0	64.6	33.1	30.2	30.57	31.44	32.45
30.0	81.6	68.2	42.3	32.0	31.56	32.15	33.03
35.0	84.3	73.2	57.5	39.3	34.60	34.07	34.48
40.0	86.7	76.8	64.9	49.5	39.62	36.87	36.40
45.0	88.7	79.7	69.6	57.4	46.13	40.70	38.91
50.0	90.6	82.2	73.2	63.0	52.5	45.30	42.00
55.0	92.2	84.3	76.1	67.2	57.9	50.1	45.50
60.0	93.8	86.1	78.5	70.5	62.2	54.6	49.17
65.0	95.2	87.8	80.6	73.3	65.8	58.5	52.8
70.0	96.5	89.3	82.5	75.6	68.7	62.0	56.2
75.0	97.7	90.8	84.2	77.7	71.2	64.9	59.3
80.0	98.9	92.1	85.7	79.5	73.4	67.5	62.1
85.0	99.9	93.3	87.1	81.1	75.4	69.8	64.5
90.0	101.0	94.4	88.3	82.6	77.1	71.8	66.8
95.0	101.9	95.4	89.5	83.9	78.6	73.6	68.8
100.0	102.9	96.4	90.6	85.2	80.1	75.2	70.5

Table 11.   Kinematic viscosity of D_2O $(10^{-6} m^2/s)$

P(MPa) \ T(°C)	3.79	25.0	50.0	75.0	100.0	150.0	200.0	250.0	300.0
0.1	1.888	0.9915	0.5943	0.4106	0.3092	25.39	32.48	40.51	49.46
0.5	1.887	0.9911	0.5943	0.4107	0.3093	0.2065	6.28	7.94	9.77
1.0	1.885	0.9907	0.5943	0.4107	0.3094	0.2066	3.003	3.865	4.802
2.5	1.879	0.9895	0.5942	0.4109	0.3097	0.2069	0.1587	1.412	1.820
5.0	1.870	0.9876	0.5941	0.4113	0.3102	0.2074	0.1592	0.1335	0.819
7.5	1.861	0.9857	0.5940	0.4116	0.3106	0.2079	0.1596	0.1339	0.4742
10.0	1.852	0.9838	0.5939	0.4120	0.3111	0.2084	0.1601	0.1344	0.1196
12.5	1.843	0.9820	0.5938	0.4123	0.3116	0.2088	0.1605	0.1349	0.1202
15.0	1.835	0.9802	0.5937	0.4127	0.3120	0.2093	0.1610	0.1353	0.1207
17.5	1.827	0.9785	0.5936	0.4130	0.3125	0.2098	0.1614	0.1357	0.1212
20.0	1.819	0.9768	0.5936	0.4133	0.3129	0.2102	0.1619	0.1361	0.1217
22.5	1.811	0.9751	0.5935	0.4137	0.3134	0.2107	0.1623	0.1365	0.1221
25.0	1.803	0.9735	0.5934	0.4140	0.3138	0.2111	0.1627	0.1369	0.1226
27.5	1.796	0.9720	0.5934	0.4144	0.3143	0.2116	0.1631	0.1373	0.1230
30.0	1.789	0.9704	0.5933	0.4147	0.3147	0.2120	0.1635	0.1377	0.1234
35.0	1.775	0.9675	0.5933	0.4153	0.3155	0.2129	0.1643	0.1384	0.1241
40.0	1.762	0.9647	0.5932	0.4160	0.3164	0.2138	0.1651	0.1391	0.1248
45.0	1.750	0.9621	0.5932	0.4166	0.3172	0.2146	0.1658	0.1398	0.1254
50.0	1.739	0.9597	0.5931	0.4173	0.3180	0.2154	0.1665	0.1404	0.1260
55.0	1.728	0.9573	0.5931	0.4179	0.3189	0.2162	0.1672	0.1410	0.1266
60.0	1.718	0.9551	0.5932	0.4185	0.3196	0.2170	0.1679	0.1416	0.1271
65.0	1.709	0.9531	0.5932	0.4192	0.3204	0.2178	0.1686	0.1422	0.1276
70.0	1.700	0.9512	0.5933	0.4198	0.3212	0.2185	0.1693	0.1428	0.1280
75.0	1.692	0.9494	0.5934	0.4204	0.3220	0.2193	0.1699	0.1433	0.1285
80.0	1.685	0.9478	0.5935	0.4210	0.3227	0.2200	0.1705	0.1438	0.1289
85.0	1.678	0.9462	0.5936	0.4216	0.3234	0.2207	0.1711	0.1443	0.1293
90.0	1.672	0.9448	0.5937	0.4222	0.3242	0.2214	0.1717	0.1448	0.1296
95.0	1.667	0.9436	0.5939	0.4228	0.3249	0.2221	0.1723	0.1452	0.1300
100.0	1.662	0.9424	0.5941	0.4234	0.3256	0.2227	0.1729	0.1457	0.1303

P(MPa) \ T(°C)	350.0	375.0	400.0	425.0	450.0	475.0	500.0
0.1	59.3	64.6	70.0	75.7	81.6	87.7	93.9
0.5	11.76	12.82	13.93	15.07	16.25	17.48	18.74
1.0	5.82	6.36	6.91	7.49	8.09	8.71	9.34
2.5	2.250	2.474	2.706	2.945	3.190	3.443	3.704
5.0	1.058	1.179	1.302	1.428	1.557	1.689	1.824
7.5	0.657	0.745	0.833	0.922	1.012	1.104	1.197
10.0	0.4535	0.526	0.598	0.668	0.739	0.811	0.884
12.5	0.3273	0.3934	0.4553	0.516	0.575	0.635	0.696
15.0	0.2368	0.3026	0.3596	0.4135	0.4661	0.518	0.570
17.5	0.1112	0.235	0.290	0.340	0.3879	0.4347	0.4810
20.0	0.1124	0.1797	0.237	0.285	0.3292	0.3720	0.4141
22.5	0.1134	0.1200	0.1949	0.242	0.2835	0.3233	0.3621
25.0	0.1142	0.1098	0.1595	0.207	0.2470	0.2845	0.3207
27.5	0.1148	0.1114	0.1299	0.1784	0.2173	0.2529	0.2869
30.0	0.1154	0.1125	0.1143	0.1551	0.1928	0.2268	0.2590
35.0	0.1164	0.1140	0.1127	0.1253	0.1563	0.1870	0.2160
40.0	0.1172	0.1151	0.1140	0.1169	0.1343	0.1596	0.1853
45.0	0.1179	0.1159	0.1149	0.1160	0.1242	0.1420	0.1636
50.0	0.1185	0.1166	0.1157	0.1163	0.1206	0.1320	0.1488
55.0	0.1191	0.1171	0.1163	0.1166	0.1193	0.1267	0.1393
60.0	0.1195	0.1176	0.1168	0.1170	0.1189	0.1240	0.1333
65.0	0.1200	0.1180	0.1171	0.1173	0.1188	0.1226	0.1295
70.0	0.1204	0.1184	0.1175	0.1175	0.1188	0.1217	0.1271
75.0	0.1207	0.1187	0.1177	0.1177	0.1188	0.1212	0.1255
80.0	0.1210	0.1190	0.1179	0.1179	0.1188	0.1208	0.1244
85.0	0.1213	0.1192	0.1181	0.1180	0.1187	0.1205	0.1236
90.0	0.1216	0.1194	0.1183	0.1180	0.1187	0.1202	0.1229
95.0	0.1218	0.1196	0.1184	0.1181	0.1186	0.1200	0.1223
100.0	0.1220	0.1198	0.1185	0.1181	0.1185	0.1197	0.1218

Table 12.   Thermal conductivity of D_2O $(10^{-3}W/(m \cdot K))$

p(MPa) \ T(°C)	3.79	25.0	50.0	75.0	100.0	150.0	200.0	250.0	300.0
0.1	565	595	618	631	636	29.04	33.77	38.93	44.49
0.5	565	595	618	632	636	625	34.70	39.47	44.85
1.0	565	595	619	632	636	625	36.27	40.28	45.35
2.5	566	596	619	633	637	626	593	43.94	47.33
5.0	567	597	621	634	639	628	595	542	52.9
7.5	569	599	622	635	640	629	596	545	64.3
10.0	570	600	623	636	641	631	598	547	475.5
12.5	572	601	624	638	642	632	600	550	479.7
15.0	573	603	626	639	644	633	602	552	483.7
17.5	575	604	627	640	645	635	604	555	487.5
20.0	576	605	628	641	646	636	605	557	491.2
22.5	578	607	629	642	647	638	607	559	494.7
25.0	579	608	631	644	649	639	609	562	498.1
27.5	580	609	632	645	650	641	610	564	501
30.0	582	610	633	646	651	642	612	566	505
35.0	585	613	635	648	654	645	615	570	511
40.0	587	615	638	651	656	647	619	574	517
45.0	590	618	640	653	658	650	622	578	522
50.0	593	620	642	655	661	653	625	582	528
55.0	596	623	645	658	663	655	628	586	533
60.0	598	625	647	660	665	658	631	590	538
65.0	601	627	649	662	668	660	634	593	542
70.0	604	630	651	664	670	663	637	597	547
75.0	606	632	654	666	672	665	640	600	551
80.0	609	635	656	669	674	668	642	604	556
85.0	611	637	658	671	677	670	645	607	560
90.0	614	639	660	673	679	673	648	610	564
95.0	616	641	662	675	681	675	651	614	568
100.0	619	644	665	677	683	677	653	617	572

p(MPa) \ T(°C)	350.0	375.0	400.0	425.0	450.0	475.0	500.0	550.0
0.1	50.4	53.5	56.7	59.9	63.3	66.7	70.1	77.2
0.5	50.7	53.8	56.9	60.1	63.5	66.8	70.3	77.3
1.0	51.0	54.1	57.2	60.4	63.7	67.1	70.5	77.5
2.5	52.4	55.2	58.2	61.3	64.6	67.9	71.3	78.2
5.0	55.5	57.8	60.4	63.3	66.3	69.5	72.8	79.6
7.5	60.4	61.5	63.4	65.8	68.3	71.5	74.6	81.2
10.0	68.0	66.7	67.4	69.0	71.3	73.9	76.8	83.1
12.5	80.4	74.3	72.7	73.1	74.7	76.8	79.4	85.2
15.0	103	85.6	79.9	78.4	78.8	80.3	82.4	87.7
17.5	393	103	89.6	85.0	83.8	84.3	85.8	90.4
20.0	401	137	103	93.3	89.8	89.1	89.8	93.5
22.5	408	349	122	104	97.0	94.6	94.3	96.9
25.0	414	370	152	117	105.7	101.0	99.4	100.6
27.5	420	370	206	135	116.1	108.3	105.1	104.7
30.0	425	376	279	159	128.6	116.8	111.6	109.1
35.0	436	390	332	227	161.8	137.5	126.7	119.2
40.0	445	403	353	284	205	164.0	145.2	130.8
45.0	453	414	369	314	247	194.8	166.8	144.0
50.0	461	424	382	335	279	226	190.4	158.5
55.0	469	433	394	351	303	253	214	174.0
60.0	476	441	404	364	321	276	237	190.0
65.0	482	449	414	376	337	295	257	206
70.0	488	456	423	387	350	312	275	222
75.0	494	463	431	397	362	326	291	237
80.0	500	470	439	406	373	339	306	251
85.0	506	476	446	415	383	350	319	265
90.0	511	482	453	422	392	361	331	278
95.0	516	488	459	430	400	371	342	290
100.0	521	494	466	437	408	380	352	301

Table 13. Thermal diffusivity of D_2O ($10^{-6} m^2/s$)

P(MPa) \ T(°C)	3.79	25.0	50.0	75.0	100.0	150.0	200.0	250.0	300.0
0.1	0.1213	0.1270	0.1337	0.1394	0.1437	27.21	35.31	44.45	54.7
0.5	0.1214	0.1270	0.1338	0.1395	0.1438	0.1472	6.55	8.49	10.62
1.0	0.1215	0.1271	0.1338	0.1395	0.1438	0.1473	2.955	3.987	5.11
2.5	0.1217	0.1273	0.1340	0.1397	0.1440	0.1475	0.1435	1.291	1.800
5.0	0.1222	0.1277	0.1343	0.1400	0.1443	0.1479	0.1441	0.1323	0.704
7.5	0.1227	0.1281	0.1346	0.1403	0.1446	0.1483	0.1446	0.1333	0.343
10.0	0.1232	0.1284	0.1349	0.1406	0.1449	0.1487	0.1452	0.1343	0.1112
12.5	0.1237	0.1288	0.1352	0.1408	0.1452	0.1490	0.1457	0.1353	0.1136
15.0	0.1242	0.1292	0.1355	0.1411	0.1455	0.1494	0.1462	0.1362	0.1158
17.5	0.1247	0.1295	0.1358	0.1414	0.1458	0.1498	0.1468	0.1371	0.1178
20.0	0.1251	0.1299	0.1361	0.1417	0.1461	0.1501	0.1473	0.1379	0.1197
22.5	0.1256	0.1302	0.1364	0.1419	0.1464	0.1505	0.1478	0.1387	0.1214
25.0	0.1261	0.1306	0.1367	0.1422	0.1466	0.1508	0.1482	0.1395	0.1230
27.5	0.1266	0.1309	0.1370	0.1425	0.1469	0.1512	0.1487	0.1403	0.1245
30.0	0.1270	0.1312	0.1373	0.1427	0.1472	0.1515	0.1492	0.1410	0.1259
35.0	0.1279	0.1319	0.1378	0.1433	0.1477	0.1522	0.1501	0.1424	0.1286
40.0	0.1288	0.1326	0.1384	0.1438	0.1483	0.1529	0.1510	0.1438	0.1310
45.0	0.1297	0.1332	0.1389	0.1443	0.1488	0.1535	0.1519	0.1451	0.1331
50.0	0.1305	0.1338	0.1394	0.1448	0.1493	0.1542	0.1527	0.1463	0.1352
55.0	0.1313	0.1344	0.1399	0.1453	0.1498	0.1548	0.1535	0.1474	0.1370
60.0	0.1320	0.1350	0.1405	0.1457	0.1503	0.1554	0.1543	0.1485	0.1388
65.0	0.1327	0.1356	0.1410	0.1462	0.1508	0.1560	0.1551	0.1496	0.1404
70.0	0.1334	0.1362	0.1415	0.1467	0.1512	0.1566	0.1559	0.1506	0.1419
75.0	0.1340	0.1367	0.1420	0.1471	0.1517	0.1572	0.1566	0.1516	0.1434
80.0	0.1346	0.1373	0.1425	0.1476	0.1522	0.1577	0.1573	0.1525	0.1448
85.0	0.1351	0.1378	0.1429	0.1480	0.1526	0.1583	0.1580	0.1535	0.1461
90.0	0.1357	0.1383	0.1434	0.1485	0.1531	0.1589	0.1587	0.1543	0.1473
95.0	0.1362	0.1389	0.1439	0.1489	0.1535	0.1594	0.1594	0.1552	0.1485
100.0	0.1366	0.1394	0.1443	0.1493	0.1539	0.1599	0.1601	0.1560	0.1496

P(MPa) \ T(°C)	350.0	375.0	400.0	425.0	450.0	475.0	500.0	550.0
0.1	66.2	72.3	78.8	85.6	92.6	99.9	107.6	123.6
0.5	12.97	14.23	15.55	16.92	18.35	19.83	21.4	24.6
1.0	6.32	6.97	7.64	8.34	9.07	9.82	10.60	12.23
2.5	2.33	2.61	2.90	3.20	3.50	3.81	4.14	4.81
5.0	1.010	1.165	1.323	1.483	1.647	1.814	1.985	2.34
7.5	0.573	0.686	0.800	0.915	1.032	1.150	1.270	1.515
10.0	0.357	0.450	0.541	0.633	0.726	0.819	0.914	1.107
12.5	0.226	0.309	0.388	0.466	0.544	0.622	0.702	0.863
15.0	0.1312	0.215	0.286	0.355	0.423	0.492	0.562	0.702
17.5	0.0661	0.144	0.213	0.277	0.338	0.400	0.462	0.587
20.0	0.0770	0.0838	0.158	0.218	0.275	0.332	0.388	0.502
22.5	0.0845	0.0166	0.112	0.172	0.226	0.279	0.331	0.436
25.0	0.0901	0.0462	0.0723	0.135	0.1872	0.237	0.286	0.384
27.5	0.0947	0.0630	0.0408	0.104	0.1554	0.203	0.249	0.342
30.0	0.0986	0.0732	0.0340	0.0791	0.1292	0.1748	0.219	0.307
35.0	0.105	0.0864	0.0574	0.0531	0.0907	0.1320	0.1725	0.253
40.0	0.110	0.0952	0.0748	0.0570	0.0714	0.1038	0.1397	0.213
45.0	0.114	0.102	0.0861	0.0690	0.0680	0.0882	0.1176	0.1842
50.0	0.1182	0.1072	0.0943	0.0800	0.0724	0.0822	0.1042	0.1626
55.0	0.1215	0.1117	0.1007	0.0888	0.0796	0.0821	0.0974	0.1472
60.0	0.1245	0.1157	0.1060	0.0958	0.0870	0.0853	0.0949	0.1365
65.0	0.1272	0.1192	0.1105	0.1017	0.0936	0.0900	0.0952	0.1294
70.0	0.1297	0.1223	0.1145	0.1066	0.0994	0.0951	0.0974	0.1250
75.0	0.1320	0.1252	0.1180	0.1110	0.1045	0.1001	0.1006	0.1225
80.0	0.1341	0.1278	0.1212	0.1148	0.1090	0.1049	0.1043	0.1215
85.0	0.1360	0.1302	0.1241	0.1182	0.1130	0.1092	0.1081	0.1216
90.0	0.1379	0.1324	0.1268	0.1214	0.1166	0.1131	0.1119	0.1226
95.0	0.1396	0.1345	0.1293	0.1243	0.1199	0.1167	0.1155	0.1242
100.0	0.1413	0.1365	0.1316	0.1269	0.1229	0.1201	0.1189	0.1262

Table 14.   Prandtl number of D_2O

P(MPa) \ T(°C)	3.79	25.0	50.0	75.0	100.0	150.0	200.0	250.0	300.0
0.1	15.6	7.81	4.44	2.95	2.15	0.933	0.920	0.912	0.904
0.5	15.5	7.80	4.44	2.94	2.15	1.40	0.960	0.936	0.920
1.0	15.5	7.80	4.44	2.94	2.15	1.40	1.02	0.969	0.940
2.5	15.4	7.77	4.43	2.94	2.15	1.40	1.11	1.09	1.01
5.0	15.3	7.73	4.42	2.94	2.15	1.40	1.10	1.01	1.16
7.5	15.2	7.70	4.41	2.93	2.15	1.40	1.10	1.00	1.38
10.0	15.0	7.66	4.40	2.93	2.15	1.40	1.10	1.00	1.08
12.5	14.9	7.62	4.39	2.93	2.15	1.40	1.10	0.997	1.06
15.0	14.8	7.59	4.38	2.92	2.14	1.40	1.10	0.993	1.04
17.5	14.7	7.55	4.37	2.92	2.14	1.40	1.10	0.990	1.03
20.0	14.5	7.52	4.36	2.92	2.14	1.40	1.10	0.987	1.02
22.5	14.4	7.49	4.35	2.91	2.14	1.40	1.10	0.984	1.01
25.0	14.3	7.46	4.34	2.91	2.14	1.40	1.10	0.981	0.997
27.5	14.2	7.43	4.33	2.91	2.14	1.40	1.10	0.979	0.988
30.0	14.1	7.39	4.32	2.91	2.14	1.40	1.10	0.976	0.980
35.0	13.9	7.35	4.30	2.90	2.14	1.40	1.09	0.972	0.965
40.0	13.7	7.28	4.29	2.89	2.13	1.40	1.09	0.967	0.953
45.0	13.5	7.22	4.27	2.89	2.13	1.40	1.09	0.964	0.942
50.0	13.3	7.17	4.25	2.88	2.13	1.40	1.09	0.960	0.932
55.0	13.2	7.12	4.24	2.88	2.13	1.40	1.09	0.957	0.924
60.0	13.0	7.07	4.22	2.87	2.13	1.40	1.09	0.954	0.916
65.0	12.9	7.03	4.21	2.87	2.13	1.40	1.09	0.951	0.909
70.0	12.7	6.99	4.19	2.86	2.12	1.40	1.09	0.948	0.902
75.0	12.6	6.94	4.18	2.86	2.12	1.39	1.08	0.945	0.896
80.0	12.5	6.90	4.17	2.85	2.12	1.39	1.08	0.943	0.890
85.0	12.4	6.87	4.15	2.85	2.12	1.39	1.08	0.940	0.885
90.0	12.3	6.83	4.14	2.84	2.12	1.39	1.08	0.938	0.880
95.0	12.2	6.80	4.13	2.84	2.12	1.39	1.08	0.936	0.875
100.0	12.2	6.76	4.12	2.84	2.11	1.39	1.08	0.934	0.871

P(MPa) \ T(°C)	350.0	375.0	400.0	425.0	450.0	475.0	500.0
0.1	0.896	0.892	0.889	0.885	0.881	0.877	0.873
0.5	0.907	0.901	0.896	0.891	0.886	0.881	0.877
1.0	0.920	0.912	0.905	0.898	0.892	0.887	0.882
2.5	0.964	0.947	0.933	0.921	0.911	0.903	0.896
5.0	1.05	1.01	0.984	0.963	0.945	0.931	0.919
7.5	1.15	1.09	1.04	1.01	0.981	0.960	0.943
10.0	1.27	1.17	1.10	1.06	1.02	0.990	0.967
12.5	1.45	1.27	1.17	1.11	1.06	1.02	0.991
15.0	1.80	1.41	1.26	1.17	1.10	1.05	1.02
17.5	1.68	1.63	1.36	1.23	1.15	1.09	1.04
20.0	1.46	2.14	1.51	1.31	1.20	1.12	1.07
22.5	1.34	7.23	1.74	1.40	1.25	1.16	1.09
25.0	1.27	2.38	2.21	1.53	1.32	1.20	1.12
27.5	1.21	1.77	3.18	1.71	1.40	1.25	1.15
30.0	1.17	1.54	3.36	1.96	1.49	1.30	1.18
35.0	1.11	1.32	1.96	2.36	1.72	1.42	1.25
40.0	1.06	1.21	1.52	2.05	1.88	1.54	1.33
45.0	1.03	1.14	1.34	1.68	1.83	1.61	1.39
50.0	1.00	1.09	1.23	1.45	1.66	1.61	1.43
55.0	0.980	1.05	1.15	1.31	1.50	1.54	1.43
60.0	0.960	1.02	1.10	1.22	1.37	1.45	1.40
65.0	0.943	0.991	1.06	1.15	1.27	1.36	1.36
70.0	0.928	0.968	1.05	1.10	1.19	1.28	1.31
75.0	0.915	0.948	0.998	1.06	1.14	1.21	1.25
80.0	0.903	0.931	0.973	1.03	1.09	1.15	1.19
85.0	0.892	0.916	0.952	0.998	1.05	1.10	1.14
90.0	0.882	0.902	0.933	0.972	1.02	1.06	1.10
95.0	0.872	0.889	0.916	0.950	0.989	1.03	1.06
100.0	0.864	0.877	0.900	0.930	0.964	0.997	1.02
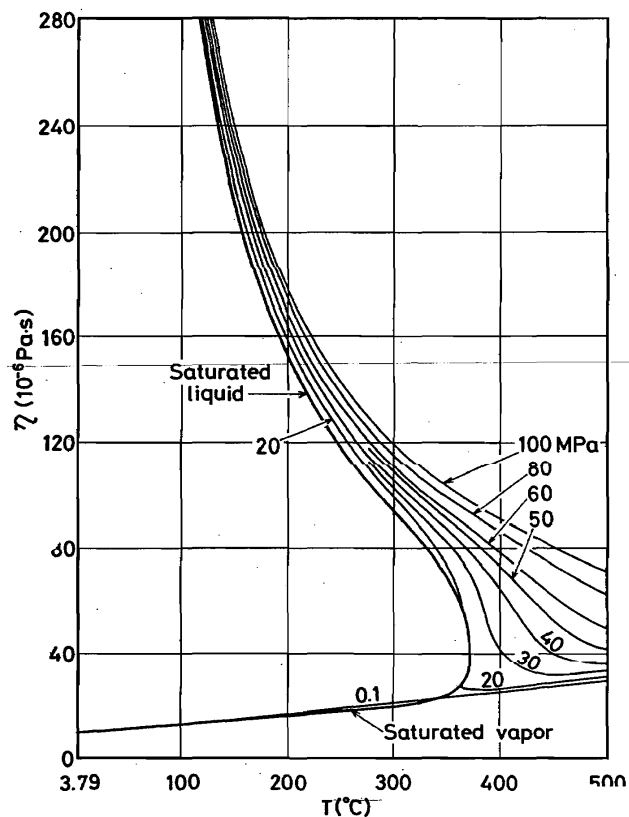
FIGURE 44. Viscosity of D_2O.
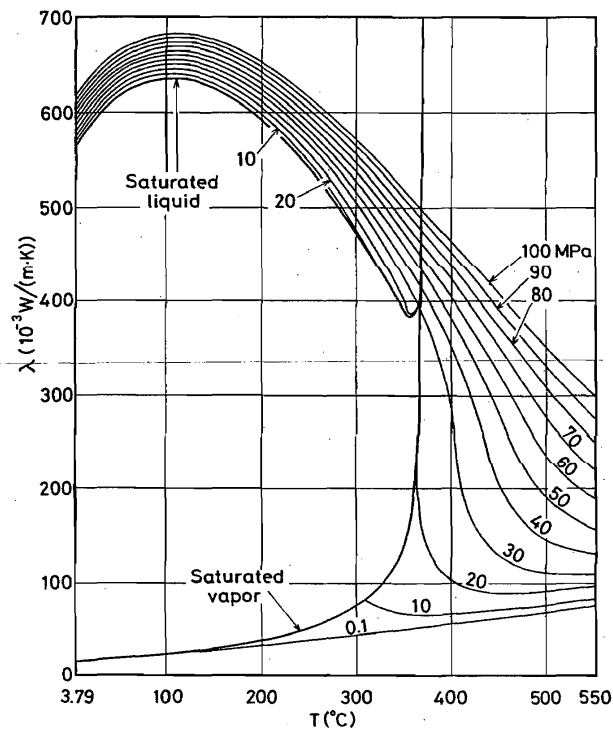
FIGURE 46. Thermal conductivity of D_2O.
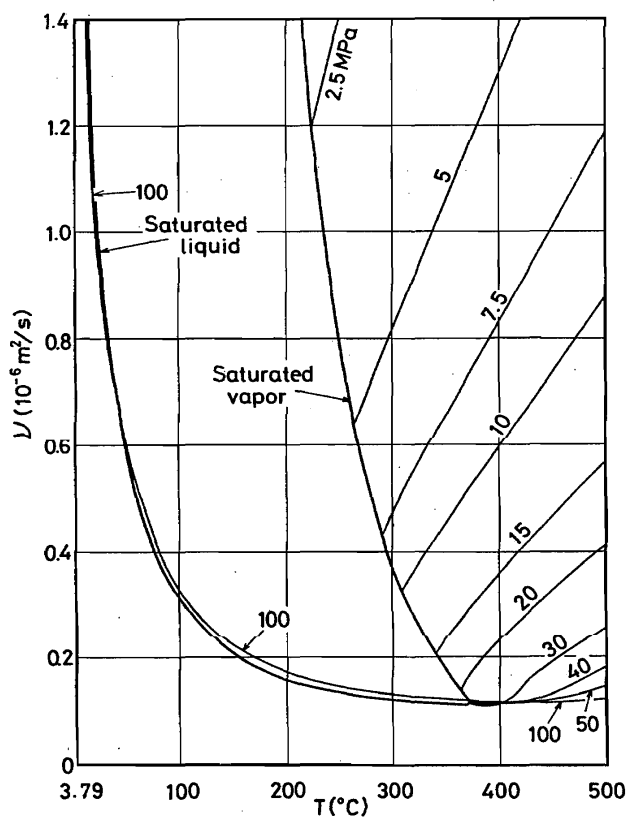
FIGURE 45. Kinematic viscosity of D_2O.
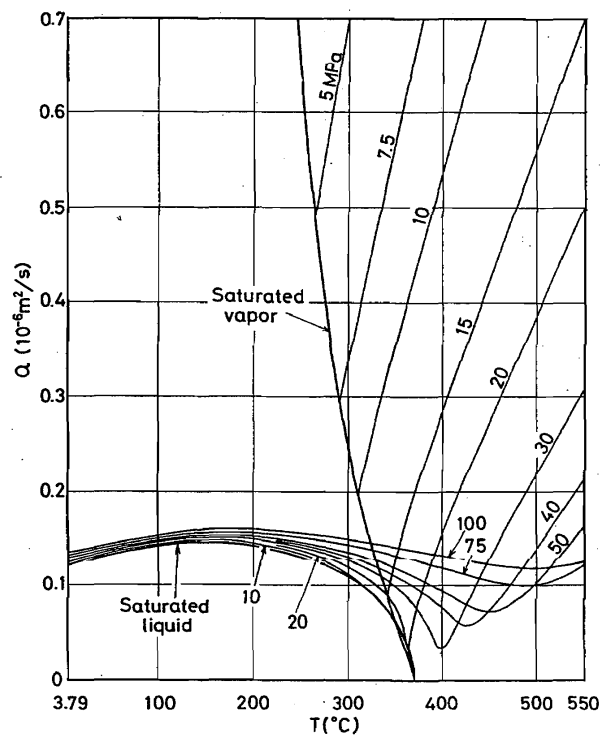
FIGURE 47. Thermal diffusivity of D_2O.
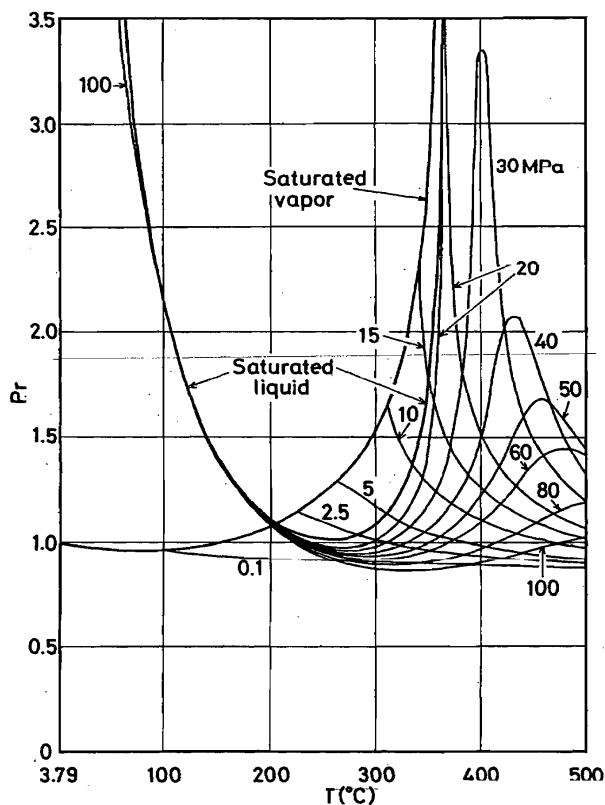
FIGURE 48. Prandtl number of D_2O.

Eqs. (6) and (7). These are shown as Tables 10–14. The same results are displayed in the form of curves in Figs. 44–48. The density, ρ was calculated with the aid of Hill's equation of state.[E3–E5] The values at saturation are given in Tables 15 and 16. The specific heat c_p calculated with Hill's equation of state was used.

8. Aids in Computer Programming

To facilitate the search for errors in computer codes we have proposed Tables 17 and 18. The tables reproduce values of the functions η/H and λ/Λ from Eqs. (6) and (7), respectively, and use the ratios $T_r = T/T_c$ and $\rho_r = \rho/\rho_c$ as the independent arguments. In this form, the computer output becomes independent of the units and pseudocritical constants employed. The result is quoted to eight significant figures.

9. Concluding Remarks

The experimental material concerning the transport properties of heavy water analyzed and synthesized in this paper is truly impressive; it is the result of intensive work over a period of fifty years, since the discovery of heavy water by Urey in 1932. Although we believe that the two equations give a fair representation of what had been measured, it is necessary to emphasize that this is so, subject to quite sizeable uncertainties in some regions. In spite of the intensity of effort expended so far, the data contain internal inconsistencies and even contradictory trends. It is still impossible to provide a scientifically based discussion of the critical enhancement of either quantity, though its existence is unmistakably revealed.

Theoretical prediction methods, such as the principle of corresponding states, were found inadequate as a basis for a comprehensive correlation or as a tool for the resolution of doubts. Additional experimental studies are urgently needed of the viscosity at high temperatures and of the thermal conductivity at temperatures below 40 °C, not to mention the critical region.

The study was proposed as a contribution of the Japanese National Committee for the Properties of Steam to the work of the International Association for the Properties of Steam. The present summary account was written at the request of the Executive Committee of the International Association for the Properties of Steam.

Table 15.   Transport properties of saturated liquid of D_2O

T (°C)	T (K)	P_s (MPa)	ρ' (kg/m³)	η' (10^{-6} Pa·s)	ν' (10^{-6} m²/s)	λ' (10^{-3} W/(m·K))	a' (10^{-6} m²/s)	Pr'
3.79	276.94	0.0006596	1105.5	2088	1.889	565	0.1213	15.6
3.80	276.95	0.0006601	1105.5	2087	1.888	565	0.1213	15.6
10.00	283.15	0.001026	1106.0	1679	1.518	575	0.1228	12.4
20.00	293.15	0.001999	1105.3	1247	1.128	589	0.1255	8.99
30.00	303.15	0.003701	1103.2	971.8	0.8808	600	0.1283	6.86
40.00	313.15	0.006549	1099.9	784.8	0.7135	610	0.1311	5.44
50.00	323.15	0.01112	1095.7	651.2	0.5943	618	0.1337	4.45
60.00	333.15	0.01820	1090.5	551.8	0.5060	625	0.1361	3.72
70.00	343.15	0.02880	1084.7	475.7	0.4386	629	0.1384	3.17
80.00	353.15	0.04423	1078.1	415.9	0.3857	633	0.1404	2.75
90.00	363.15	0.06607	1071.0	367.9	0.3435	635	0.1422	2.42
100.00	373.15	0.09625	1063.4	328.8	0.3092	636	0.1437	2.15
110.00	383.15	0.13706	1055.2	296.5	0.2810	636	0.1450	1.94
120.00	393.15	0.19115	1046.4	269.4	0.2575	635	0.1460	1.76
130.00	403.15	0.26154	1037.2	246.5	0.2377	632	0.1467	1.62
140.00	413.15	0.35167	1027.5	226.9	0.2209	629	0.1471	1.50
150.00	423.15	0.46532	1017.3	210.0	0.2065	625	0.1472	1.40
160.00	433.15	0.60669	1006.5	195.3	0.1941	620	0.1470	1.32
170.00	443.15	0.78034	995.26	182.4	0.1833	614	0.1465	1.25
180.00	453.15	0.99119	983.47	171.1	0.1739	607	0.1457	1.19
190.00	463.15	1.245	971.13	160.9	0.1657	600	0.1446	1.15
200.00	473.15	1.546	958.22	151.9	0.1585	592	0.1433	1.11
210.00	483.15	1.902	944.71	143.8	0.1522	583	0.1416	1.07
220.00	493.15	2.317	930.56	136.4	0.1466	574	0.1397	1.05
230.00	503.15	2.800	915.73	129.7	0.1416	564	0.1374	1.03
240.00	513.15	3.357	900.16	123.5	0.1372	553	0.1348	1.02
250.00	523.15	3.995	883.76	117.8	0.1333	541	0.1319	1.01
260.00	533.15	4.722	866.44	112.5	0.1298	529	0.1285	1.01
270.00	543.15	5.546	848.08	107.5	0.1267	516	0.1247	1.02
280.00	553.15	6.476	828.52	102.7	0.1240	502	0.1204	1.03
290.00	563.15	7.520	807.54	98.1	0.1215	488.2	0.1155	1.05
300.00	573.15	8.688	784.87	93.6	0.1193	473.3	0.1099	1.09
310.00	583.15	9.992	760.15	89.2	0.1173	457.7	0.1034	1.13
320.00	593.15	11.44	732.83	84.7	0.1155	441.6	0.0960	1.20
330.00	603.15	13.05	702.11	80.0	0.1139	424.9	0.0871	1.31
340.00	613.15	14.84	666.61	74.9	0.1123	407.9	0.0761	1.47
345.00	618.15	15.80	646.31	72.1	0.1115	399.5	0.0695	1.60
350.00	623.15	16.82	623.58	69.0	0.1107	391	0.0618	1.79
355.00	628.15	17.89	597.40	65.7	0.1099	385	0.0527	2.09
360.00	633.15	19.02	565.68	61.6	0.1090	382	0.0415	2.63
361.00	634.15	19.25	558.32	60.7	0.1088	383	0.0389	2.79
362.00	635.15	19.48	550.49	59.8	0.1086	385	0.0363	2.99
363.00	636.15	19.72	542.08	58.7	0.1084	388	0.0334	3.24
364.00	637.15	19.96	532.98	57.6	0.1082	392	0.0305	3.55
365.00	638.15	20.21	522.99	56.4	0.1079	399	0.0273	3.95
366.00	639.15	20.45	511.83	55.1	0.1077	408	0.0239	4.51
367.00	640.15	20.70	499.04	53.6	0.1074	422	0.0202	5.32
368.00	641.15	20.95	483.81	51.9	0.1072	443	0.0161	6.67
369.00	642.15	21.21	464.32	49.6	0.1069	478	0.0113	9.45
370.00	643.15	21.47	434.88	46.4	0.1068	538	0.0056	19.2

Table 16.   Transport properties of saturated vapor of D_2O

T (°C)	T (K)	P_s (MPa)	ρ'' (kg/m³)	η'' (10^{-6}Pa·s)	ν'' (10^{-6}m²/s)	λ'' (10^{-3}W/(m·K))	a'' (10^{-6}m²/s)	Pr''
3.79	276.94	0.0006596	0.005741	9.60	1672	16.53	1683	0.994
3.80	276.95	0.0006601	0.005745	9.60	1671	16.53	1682	0.994
10.00	283.15	0.001026	0.008737	9.76	1117	16.99	1132	0.987
20.00	293.15	0.001999	0.016445	10.03	610	17.75	624	0.978
30.00	303.15	0.003701	0.029461	10.32	350	18.52	361	0.971
40.00	313.15	0.006549	0.050498	10.63	210	19.33	218	0.967
50.00	323.15	0.01112	0.083189	10.94	131.5	20.2	136.4	0.964
60.00	333.15	0.01820	0.13224	11.27	85.2	21.0	88.5	0.962
70.00	343.15	0.02880	0.20356	11.60	57.0	21.9	59.2	0.962
80.00	353.15	0.04423	0.30439	11.94	39.2	22.8	40.7	0.962
90.00	363.15	0.06607	0.44341	12.28	27.7	23.8	28.7	0.963
100.00	373.15	0.09625	0.63082	12.62	20.0	24.8	20.7	0.965
110.00	383.15	0.1371	0.87844	12.96	14.76	25.88	15.24	0.968
120.00	393.15	0.1911	1.1998	13.31	11.09	27.01	11.41	0.972
130.00	403.15	0.2615	1.6101	13.65	8.48	28.19	8.67	0.978
140.00	413.15	0.3517	2.1266	13.99	6.58	29.45	6.68	0.985
150.00	423.15	0.4653	2.7686	14.33	5.18	30.78	5.21	0.994
160.00	433.15	0.6067	3.5574	14.67	4.123	32.20	4.100	1.01
170.00	443.15	0.7803	4.5172	15.00	3.321	33.72	3.257	1.02
180.00	453.15	0.9912	5.6745	15.33	2.702	35.34	2.606	1.04
190.00	463.15	1.245	7.0594	15.66	2.219	37.10	2.100	1.06
200.00	473.15	1.546	8.7058	15.99	1.837	39.00	1.702	1.08
210.00	483.15	1.902	10.652	16.32	1.532	41.07	1.386	1.10
220.00	493.15	2.317	12.942	16.64	1.286	43.36	1.135	1.13
230.00	503.15	2.800	15.627	16.98	1.086	45.92	0.933	1.16
240.00	513.15	3.357	18.768	17.31	0.922	48.79	0.770	1.20
250.00	523.15	3.995	22.434	17.66	0.787	52.0	0.638	1.23
260.00	533.15	4.722	26.715	18.01	0.674	55.8	0.530	1.27
270.00	543.15	5.546	31.717	18.39	0.580	60.1	0.4405	1.32
280.00	553.15	6.476	37.577	18.78	0.500	64.8	0.3650	1.37
290.00	563.15	7.520	44.472	19.21	0.4319	69.8	0.2994	1.44
300.00	573.15	8.688	52.640	19.68	0.3738	75.2	0.2425	1.54
310.00	583.15	9.992	62.411	20.20	0.3237	81.9	0.1952	1.66
320.00	593.15	11.44	74.267	20.81	0.2802	90.9	0.1558	1.80
330.00	603.15	13.05	88.958	21.53	0.2421	102.7	0.1219	1.99
340.00	613.15	14.84	107.77	22.45	0.2083	118.8	0.0914	2.28
345.00	618.15	15.80	119.44	23.02	0.1928	129.4	0.0772	2.50
350.00	623.15	16.82	133.31	23.7	0.1779	143	0.0634	2.80
355.00	628.15	17.89	150.36	24.6	0.1634	162	0.0500	3.27
360.00	633.15	19.02	172.62	25.7	0.1491	191	0.0365	4.08
361.00	634.15	19.25	178.05	26.0	0.1462	199	0.0338	4.33
362.00	635.15	19.48	183.93	26.4	0.1433	209	0.0310	4.63
363.00	636.15	19.72	190.38	26.7	0.1403	220	0.0281	4.99
364.00	637.15	19.96	197.51	27.1	0.1373	233	0.0252	5.45
365.00	638.15	20.21	205.53	27.6	0.1342	249	0.0222	6.06
366.00	639.15	20.45	214.73	28.1	0.1310	269	0.0190	6.90
367.00	640.15	20.70	225.61	28.8	0.1276	295	0.0156	8.18
368.00	641.15	20.95	239.06	29.6	0.1240	330	0.0119	10.4
369.00	642.15	21.21	257.14	30.8	0.1199	382	0.00788	15.2
370.00	643.15	21.47	286.62	32.9	0.1148			

Table 17. Check-values of the dynamic viscosity ratio η/H in terms of T_r, ρ_r. All entries are dimensionless.

REDUCED ABSOLUTE TEMPERATURE (T_r)	REDUCED DENSITY (ρ_r)	REDUCED VISCOSITY (η/H)
0.43100000D+00	0.30900000D+01	0.36912317D+02
0.43100000D+00	0.32300000D+01	0.34153155D+02
0.50000000D+00	0.20000000D-03	0.19729842D+00
0.50000000D+00	0.30700000D+01	0.12060491D+02
0.50000000D+00	0.31800000D+01	0.12467941D+02
0.60000000D+00	0.27000000D-02	0.23658290D+00
0.60000000D+00	0.29500000D+01	0.52437250D+01
0.60000000D+00	0.30700000D+01	0.57570400D+01
0.75000000D+00	0.29500000D-01	0.29514798D+00
0.75000000D+00	0.26500000D+01	0.26275044D+01
0.75000000D+00	0.28300000D+01	0.30417584D+01
0.90000000D+00	0.80000000D-01	0.36854726D+00
0.90000000D+00	0.16300000D+00	0.36196491D+00
0.90000000D+00	0.21600000D+01	0.16561616D+01
0.90000000D+00	0.25200000D+01	0.21041365D+01
0.10000000D+01	0.30000000D+00	0.44248168D+00
0.10000000D+01	0.70000000D+00	0.55286939D+00
0.10000000D+01	0.15500000D+01	0.11038442D+01
0.10000000D+01	0.22600000D+01	0.17569586D+01
0.11000000D+01	0.49000000D+00	0.56330381D+00
0.11000000D+01	0.98000000D+00	0.78163879D+00
0.11000000D+01	0.14700000D+01	0.11169457D+01
0.11000000D+01	0.19600000D+01	0.15001421D+01
0.12000000D+01	0.40000000D+00	0.60945391D+00
0.12000000D+01	0.80000000D+00	0.76510992D+00
0.12000000D+01	0.12000000D+01	0.99378701D+00
0.12000000D+01	0.16100000D+01	0.12711900D+01

The calculations were made utilizing 17 significant figures and the results were rounded as shown.

Table 18. Check-values of the thermal conductivity ratio λ/Λ in terms of T_r, ρ_r. All entries are dimensionless.

REDUCED ABSOLUTE TEMPERATURE (T_r)	REDUCED DENSITY (ρ_r)	REDUCED THERMAL CONDUCTIVITY (λ/Λ)
0.43100000D+00	0.30900000D+01	0.76291571D+03
0.43100000D+00	0.32300000D+01	0.83391205D+03
0.50000000D+00	0.20000000D-03	0.27006537D+02
0.50000000D+00	0.30700000D+01	0.83578642D+03
0.50000000D+00	0.31800000D+01	0.89118175D+03
0.60000000D+00	0.27000000D-02	0.35339950D+02
0.60000000D+00	0.29500000D+01	0.86124079D+03
0.60000000D+00	0.30700000D+01	0.91985909D+03
0.75000000D+00	0.29500000D-01	0.55216750D+02
0.75000000D+00	0.26500000D+01	0.79044256D+03
0.75000000D+00	0.28300000D+01	0.86967229D+03
0.90000000D+00	0.80000000D-01	0.74522283D+02
0.90000000D+00	0.16300000D+00	0.10630197D+03
0.90000000D+00	0.21600000D+01	0.62777759D+03
0.90000000D+00	0.25200000D+01	0.76105504D+03
0.10000000D+01	0.30000000D+00	0.14342200D+03
0.10000000D+01	0.70000000D+00	0.46901512D+03
0.10000000D+01	0.15500000D+01	0.50284695D+03
0.10000000D+01	0.22600000D+01	0.66874352D+03
0.11000000D+01	0.49000000D+00	0.18481346D+03
0.11000000D+01	0.98000000D+00	0.32665238D+03
0.11000000D+01	0.14700000D+01	0.43837031D+03
0.11000000D+01	0.19600000D+01	0.57201441D+03
0.12000000D+01	0.40000000D+00	0.16005940D+03
0.12000000D+01	0.80000000D+00	0.25960524D+03
0.12000000D+01	0.12000000D+01	0.36217957D+03
0.12000000D+01	0.16100000D+01	0.47174773D+03
0.12700000D+01	0.30000000D+00	0.14524991D+03
0.12700000D+01	0.60000000D+00	0.21199630D+03
0.12700000D+01	0.95000000D+00	0.29925147D+03
0.12700000D+01	0.13700000D+01	0.40935968D+03

The calculations were made utilizing 17 significant figures and the results were rounded as shown.

10. Notation

a	thermal diffusivity	[m²/s]
c_p	isobaric specific heat capacity	[J/(kg·K)]
D	diffusion coefficient	[m²/s]
P	Pressure	[MPa]
Pr	Prandtl number	[—]
T	temperature	[K]
η	viscosity	[Pa·s]
λ	thermal conductivity	[W/(m·K)]
ν	kinematic viscosity	[m²/s]
ρ	density	[kg/m³]

11. Acknowledgments

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Appendix
The International Association
for
The Properties of Steam

Release on Viscosity and Thermal Conductivity of Heavy Water Substance

September 1982

Unrestricted publication allowed in all countries.

Issued by the International Association for the Properties of Steam.

President, Professor Ichimatsu Tanishita
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Executive Secretary, Dr. Howard J. White, Jr.
Office of Standard Reference Data
National Bureau of Standards
Washington, DC 20234, USA

This Release on the transport properties of heavy water (deuterium oxide) has been authorized by the International Association for the Properties of Steam for issue by its Secretariat. This Release contains in the accompanying Appendices the *International Representation of the Viscosity of Heavy Water Substance* (Deuterium Oxide, D_2O) and the *International Representation of the Thermal Conductivity of Heavy Water Substance* (Deuterium Oxide, D_2O), 1982.

The material included in the Release was prepared by Working Group II of IAPS under the chairmanship of J. Kestin, Professor of Engineering at Brown University, Providence RI, USA. In accordance with the Statutes of IAPS, the material in the Release has been circulated to and approved by the Members of IAPS (Canada, Czechoslovakia, Federal Republic of Germany, France, Japan, United Kingdom, United States of America, and Union of Soviet Socialist Republics).

Further information can be obtained from the Executive Secretary of IAPS:

Dr. Howard J. White, Jr.
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Washington DC, 20234, USA.

Attachments: Appendix A
               Appendix B

Appendix A

International Representation of the Viscosity of Heavy Water Substance (Deuterium Oxide, D_2O)

1982

IAPS Working Group II (on Transport Properties) has critically examined the experimental results on the viscosity of liquid and gaseous heavy water and recommends that the values implied by the equation given below should be used for this property. This equation represents the said quantity as a function of temperature and density. For a conversion to a representation as a function of temperature and pressure, values of density should be computed from the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Heavy Water Substance, contained in the following reference: P. G. Hill, R. D. C. MacMillan, and V. Lee, "A Fundamental Equation of State for Heavy Water", J. Phys. Chem. Ref. Data **11**, 1 (1982); Errata, **12**, 1065 (1983).

The recommended equation is

$$\eta = \eta_0(T_r)\cdot\exp\left\{\rho_r\left[\sum_{i=0}^{5}\sum_{j=0}^{6} A_{ij}(T_r^{-1} - 1)^i(\rho_r - 1)^j\right]\right\},$$

where (A1)

$$\eta_0(T_r) = H\cdot T_r^{1/2}\left(\sum_{k=0}^{3} B_k\cdot T_r^{-k}\right)^{-1}.$$ (A2)

The reduced variables are

$$T_r = T/T^* \quad \text{and} \quad \rho_r = \rho/\rho^*,$$ (A3)

and the meaning of the symbols is as follows:

η dynamic viscosity
T temperature on the International Practical Temperature Scale of 1968
ρ density
T^* reference temperature
ρ^* reference density.

The reference constants T^* and ρ^* are close, but not necessarily equal, to the actual critical parameters of heavy water. For the purpose of this representation, they play the part of correlation constants and need not be amended when improved values of the actual critical constants become available.

The constants appearing in Eqs. (A1), (A2), and (A3) are listed below.

$T^* = 643.89$ K
$\rho^* = 358$ kg/m^3
$H = 55.2651 \times 10^{-6}$ Pa·s

The coefficients A_{ij}

$i =$	0	1	2	3	4	5
$j = 0$	0.4864 192	− 0.2448 372	− 0.8702 035	0.8716 056	− 1.0511 26	0.3458 395
1	0.3509 007	1.3154 36	1.2977 52	1.3534 48	0.0	0.0
2	− 0.2847 572	− 1.0370 26	− 1.2878 46	0.0	0.0	− 0.0214 8229
3	0.0701 3759	0.4660 127	0.2292 075	− 0.4857 462	0.0	0.0
4	0.0164 1220	− 0.0288 4911	0.0	0.1607 171	0.0	− 0.0096 0384 6
5	− 0.0116 3815	− 0.0082 3958 7	0.0	0.0	0.0	0.0045 5991 4
6	0.0	0.0	0.0	− 0.0038 8665 9	0.0	0.0

The coefficients B_k

$B_0 =$	1.0000 0
$B_1 =$	0.9406 95
$B_2 =$	0.5783 77
$B_3 =$	− 0.2020 44

FIGURE A1. Tolerances of the representation of the viscosity of heavy water.

Range

The representation of the viscosity of heavy water by Eqs. (A1), (A2), and (A3) together with the numerial constants listed above is valid in the rectangle defined by

$$0 \text{ MPa} \leqslant P \leqslant 100 \text{ MPa}$$

$$277 \text{ K (melting point)} \leqslant T \leqslant 775 \text{ K}.$$

Tolerances

The equation represents the viscosity within an uncertainty of $\pm 1\%$ to $\pm 5\%$ as defined in Fig. A1. However, no tolerances are assigned in the region contained within

$$0.995 < T_r < 1.005$$

$$0.9 < \rho_r < 1.1,$$

because critical-point effects on the viscosity are not contained in the equation.

Tables

Three tables are relevant to Appendix A. Table 10 contains recommended values of viscosity calculated at the nodal points of the international grid accepted for the publications emanating from IAPS. Table A1 contains recommended values of viscosity calculated along the saturation line. Table 17 contains selected values of the function η/H in terms of T_r and ρ_r quoted to eight significant digits to serve as an aid in checking computer programs.

Table A1. Recommended values of the dynamic viscosity of D₂O along the saturation line, η in units of 10⁻⁶ Pa·s, temperature T in °C, pressure P in MPa.

T	P	η'	η"
3.79	0.0006596	2088	9.60
3.80	0.0006601	2087	9.60
10.00	0.001026	1679	9.76
20.00	0.001999	1247	10.03
30.00	0.003701	971.8	10.32
40.00	0.006549	784.8	10.63
50.00	0.01112	651.2	10.94
60.00	0.01820	551.8	11.27
70.00	0.02880	475.7	11.60
80.00	0.04423	415.9	11.94
90.00	0.06607	367.9	12.28
100.00	0.09625	328.8	12.62
110.00	0.13706	296.5	12.96
120.00	0.19115	269.4	13.31
130.00	0.26154	246.5	13.65
140.00	0.35167	226.9	13.99
150.00	0.46532	210.0	14.33
160.00	0.60669	195.3	14.67
170.00	0.78034	182.4	15.00
180.00	0.99119	171.1	15.33
190.00	1.245	160.9	15.66
200.00	1.546	151.9	15.99
210.00	1.902	143.8	16.32
220.00	2.317	136.4	16.64
230.00	2.800	129.7	16.98
240.00	3.357	123.5	17.31
250.00	3.995	117.8	17.66
260.00	4.722	112.5	18.01
270.00	5.546	107.5	18.39
280.00	6.476	102.7	18.78
290.00	7.520	98.1	19.21
300.00	8.688	93.6	19.68
310.00	9.992	89.2	20.20
320.00	11.44	84.7	20.81
330.00	13.05	80.0	21.55
340.00	14.84	74.9	22.45
345.00	15.80	72.1	23.02
350.00	16.82	69.0	23.7
355.00	17.89	65.7	24.6
360.00	19.02	61.6	25.7
361.00	19.25	60.7	26.0
362.00	19.48	59.8	26.4
363.00	19.72	58.7	26.7
364.00	19.96	57.6	27.1
365.00	20.21	56.4	27.6
366.00	20.45	55.1	28.1
367.00	20.70	53.6	28.8
368.00	20.95	51.9	29.6
369.00	21.21	49.6	30.8
370.00	21.47	46.4	32.9

Appendix B

International Representation of the Thermal Conductivity of Heavy Water Substance (Deuterium Oxide, D₂O) 1982

IAPS Working Group II (on Transport Properties) has critically examined the experimental results on the thermal conductivity of liquid and gaseous heavy water and recommends that the values implied by the equation given below should be used for this property. The equation represents the said quantity as a function of temperature and density. For a conversion to a representation as a function of temperature and pressure, values of density should be computed from the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Heavy Water Substance, contained in the following reference: P. G. Hill, R. D. C. MacMillan, and V. Lee, "A Fundamental Equation of State for Heavy Water," J. Phys. Chem. Ref. Data **11**, 1 (1982); Errata, **12**, 1065 (1983).

The recommended equation is

$$\lambda = \Lambda \left[\lambda_0 + \Delta\lambda + \Delta\lambda_c + \Delta\lambda_L \right], \tag{B1}$$

where

$$\lambda_0 = \sum_{i=0}^{5} A_i T_r^{i}, \tag{B2}$$

$$\Delta\lambda = B_0[1 - \exp(B_e \rho_r)] + \sum_{j=1}^{4} B_j \rho_r^{j}, \tag{B3}$$

$$\Delta\lambda_c = C_\lambda f_1(T_r) f_2(\rho_r)\left(1 + [f_2(\rho_r)]^2\left\{\frac{C_2[f_1(T_r)]^4}{f_3(T_r)}\right.\right.$$

$$\left.\left. + \frac{3.5 f_2(\rho_r)}{f_4(T_r)}\right\}\right),\qquad\text{(B4)}$$

$$\Delta\lambda_L = D_1[f_1(T_r)]^{1.2}\left\{1 - \exp\left[-\left(\frac{\rho_r}{2.5}\right)^{10}\right]\right\},\qquad\text{(B5)}$$

and

$$f_1(T_r) = \exp(C_{T1}T_r + C_{T2}T_r^2),\qquad\text{(B6)}$$

$$f_2(\rho_r) = \exp[C_{R1}(\rho_r - 1)^2]$$
$$+ C_{R2}\exp[C_{R3}(\rho_r - \rho_{r1})^2],\qquad\text{(B7)}$$

$$f_3(T_r) = 1 + \exp[60(\tau - 1) + 20],\qquad\text{(B8)}$$

$$f_4(T_r) = 1 + \exp[100(\tau - 1) + 15],\qquad\text{(B9)}$$

$$\tau = \frac{T_r}{|T_r - 1.1| + 1.1}.\qquad\text{(B10)}$$

The reduced variables are

$$T_r = T/T^* \quad\text{and}\quad \rho_r = \rho/\rho^*,\qquad\text{(B11)}$$

and the meaning of the symbols is as follows:

λ thermal conductivity

T temperature on the International Practical Temperature Scale of 1968

ρ density

T^* reference temperature

ρ^* reference density.

The reference constants T^* and ρ^* are close, but not necessarily equal, to the actual critical parameters of heavy water. For the purpose of this representation, they play the part of correlation constants and need not be amended when improved values of the actual critical constants become available.

The constants appearing in Eqs. (B1)–(B11) are listed below.

$T^* = 643.89$ K
$\rho^* = 358$ kg/m^3
$\Lambda = 0.7421\,28\times10^{-3}$ W/(m·K)

$A_0 =$	1.0000 0	C_1	$=$	0.3542 96×10^5
$A_1 =$	37.3223	C_2	$=$	0.5000 00×10^{10}
$A_2 =$	22.5485			
$A_3 =$	13.0465	C_{T1}	$=$	0.1448 47
$A_4 =$	0.0	C_{T2}	$=$	$-5.6449\,3$
$A_5 =$	$-2.6073\,5$	C_{R1}	$=$	$-2.8000\,0$
		C_{R2}	$=$	$-0.0807\,3854\,3$
$B_e =$	$-2.5060\,0$	C_{R3}	$=$	-17.9430
$B_0 = -167.310$		ρ_{r1}	$=$	0.1256 98
$B_1 =$	483.656			
$B_2 = -191.039$		D_1	$=$	-741.112
$B_3 =$	73.0358			
$B_4 =$	$-7.5746\,7$			

Range

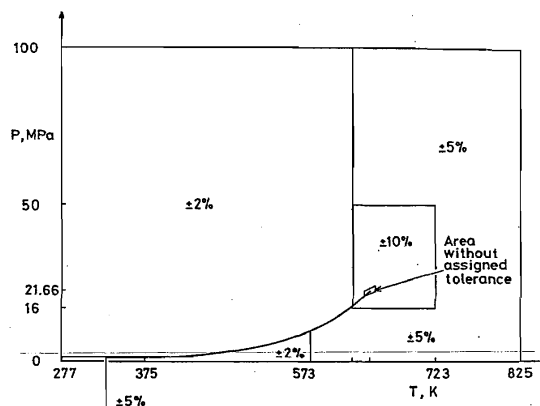The representation of the thermal conductivity of heavy water by Eqs. (B1)–(B11) together with the numerical

FIGURE B1. Tolerances of the representation of the thermal conductivity of heavy water.

Table B1. Recommended values of the thermal conductivity of D$_2$O along the saturation line, λ in units of 10^{-3} W/(m·K), temperature T in °C, pressure P in MPa.

T	P	λ'	λ''
3.79	0.0006596	565	16.53
3.80	0.0006601	565	16.53
10.00	0.001026	575	16.99
20.00	0.001999	589	17.75
30.00	0.003701	600	18.52
40.00	0.006549	610	19.33
50.00	0.01112	618	20.2
60.00	0.01820	625	21.0
70.00	0.02880	629	21.9
80.00	0.04423	633	22.8
90.00	0.06607	635	23.8
100.00	0.09625	636	24.8
110.00	0.1371	636	25.88
120.00	0.1911	635	27.01
130.00	0.2615	632	28.19
140.00	0.3517	629	29.45
150.00	0.4653	625	30.78
160.00	0.6067	620	32.20
170.00	0.7803	614	33.72
180.00	0.9912	607	35.34
190.00	1.245	600	37.10
200.00	1.546	592	39.00
210.00	1.902	583	41.07
220.00	2.317	574	43.36
230.00	2.800	564	45.92
240.00	3.357	553	48.79
250.00	3.995	541	52.0
260.00	4.722	529	55.8
270.00	5.546	516	60.1
280.00	6.476	502	64.8
290.00	7.520	488.2	69.8
300.00	8.688	473.3	75.2
310.00	9.992	457.7	81.9
320.00	11.44	441.6	90.9
330.00	13.05	424.9	102.7
340.00	14.84	407.9	118.8
345.00	15.80	399.5	129.4
350.00	16.82	391	143
355.00	17.89	385	162
360.00	19.02	382	191
361.00	19.25	383	199
362.00	19.48	385	209
363.00	19.72	388	220
364.00	19.96	392	233
365.00	20.21	399	249
366.00	20.45	408	269
367.00	20.70	422	295
368.00	20.95	443	330
369.00	21.21	478	382
370.00	21.47	538	475

constants listed above is valid in the rectangle defined by

0 MPa $\leqslant P \leqslant$ 100 MPa

277 K (melting point) $\leqslant T \leqslant$ 825 K.

Tolerances

The equation represents the thermal conductivity within an uncertainty of $\pm 2\%$ to $\pm 10\%$ as defined in Fig. D1. However, no tolerances are assigned in the region contained within

$0.99 < T_r < 1.05$

$0.8 < \rho_r < 1.2,$

because the actual thermal conductivity diverges at the critical point, while the thermal conductivity calculated from the equation remains finite at the critical point.

Tables

Three tables are relevant to Appendix B. Table 12 contains recommended values of thermal conductivity calculated at the nodal points of the international grid accepted for the publications of IAPS. Table B1 contains recommended values of thermal conductivity calculated along the saturation line. Table 18 contains selected values of the function λ / Λ in terms of T_r and ρ_r quoted to eight significant digits to serve as an aid in checking computer programs.