A Database for the Static Dielectric Constant of Water and Steam

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All reliable sources of data for the static dielectric constant or relative permittivity of water and steam, many of them unpublished or inaccessible, have been collected, evaluated, corrected when required, and converted to the ITS–90 temperature scale. The data extend over a temperature range from 238 to 873 K and over a pressure range from 0.1 MPa up to 1189 MPa. The evaluative part of this work includes a review of the different types of measurement techniques, and the corrections for frequency dependence due to the impedance of circuit components, and to electrode polarization. It also includes a detailed assessment of the uncertainty of each particular data source, as compared to other sources in the same range of pressure and temperature. Both the raw and the corrected data have been tabulated, and are also available on diskette. A comprehensive list of references to the literature is included. *©1995 American Institute of Physics and American Chemical Society.*

Key words: capacitance bridges; compilation; data evaluation; electrode polarization; ITS–90; resonant circuits; static dielectric constant; static relative permittivity; steam; supercritical steam; water.

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List of Symbols

C	capacitance
f	frequency
G	conductance
K_c	geometric constant
L	inductance
p	pressure
p_o	0.101325 MPa
Q	quality factor
T	temperature
T_b	normal boiling temperature, 373.124 K (ITS-90)
T_f	normal freezing temperature, 273.150 K
T_o	298.144 K (ITS-90)
ϵ_s,ϵ	static permittivity, or dielectric constant
ϵ'	real part of the permittivity
ϵ''	complex part of the permittivity, or dielectric loss
ϵ_∞	optical permittivity
ϵ_o	permittivity of free space
κ	specific conductivity
ρ	density, V_m molar volume
λ	wavelength
τ	dielectric relaxation time
ω	angular frequency ($\omega=2\pi/f$)

1. Introduction

Experimental determinations of the dielectric constant of pure water have been performed by many scientists since the end of the last century. In his book "Properties of Ordinary Water-Substance", N. E. Dorsey[1] quotes 47 papers reporting values for this quantity between the years 1893 and 1937. Most effort was expended to determine the frequency dependence of the dielectric constant, and it was found in that period of time that no rotational absorption band exists below 1 GHz. The temperature effect was first studied in 1893, but poor agreement was obtained prior to the establishment of the first International Temperature Scale in 1928. Only three papers were concerned with the effect of pressure, all of them revealing a small positive slope at room temperature.

More recently, Uematsu and Franck[2] presented a survey of available literature data up to 1975, including several very accurate studies in the liquid region, which superseded all previous work. Regions other than that of the liquid were investigated for the first time in this period, such as the steam and water states along the saturation curve, and the supercritical region. Results for supercritical and saturated steam obtained from the Russian literature were included, although in most of these publications the data were presented only in graphical form.

Since 1975, new results have been reported in all of these regions, and, in addition, in the supercooled liquid phase at ambient pressure. Since 1975, also, several new data collections were assembled as part of correlations for the static dielectric constant of water. We mention those of Pitzer,[3] Marsh[4] and especially, Archer and Wang.[5] The latter contains the most recent comprehensive literature survey and gives reference to all data Archer and Wang used in their correlation of the static dielectric constant of water and steam. Since this paper appeared in 1990, however, new data for saturated steam and liquid water have been obtained.

More than half of the data we have collected are contained in unpublished PhD theses, or in journals often not readily available. The purpose of this paper is to make the entire original experimental data base available in computer-accessible form. In addition, a corrected data set is presented; corrections involve updating of the temperature scale; in some cases, recalculating the pressure; and recalculating of values of the dielectric constant determined relative to another substance when necessary. Furthermore, the data sets are evaluated, sources of error are assessed, and, to the extent possible, a judgment is made about the uncertainty of each data set. This last point is important in view of the fact that the differences in the data obtained by different authors for the same thermodynamic region are, in many cases, larger than the uncertainty claimed for the individual data sets.

The focus of this work is on the static dielectric constant, that is, the real part of the relative permittivity in the limit of zero frequency. There is a large amount of experimental work devoted to the permittivity of liquid water at ambient conditions and frequencies between 1 GHz and 40 GHz.[6–8] The frequency dependence of the experimental permittivity may be represented in this range with an accuracy of 1% by the Debye function,[8]

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau} = \epsilon' + i\epsilon'', \tag{1}$$

where

$$\epsilon'(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1+\omega^2\tau^2}, \tag{2}$$

and

$$\epsilon''(\omega) = \frac{(\epsilon_s - \epsilon_\infty)\,\omega\tau}{1+\omega^2\,\tau^2}. \tag{3}$$

In Eqs. (1)–(3), $\omega=2\pi f$, f is the frequency, ϵ_s is the parameter identified with the static dielectric constant, the topic of this work, ϵ_∞ is the parameter identified with the optical permittivity at frequencies $\omega \gg 2\pi / \tau$, and τ is the relaxation time characteristic of the dipole reorientation in a changing electric field. ϵ' and ϵ'' are, respectively, the real and imaginary parts of the permittivity.

At 298.15 K, ϵ' decreases from 78.4, its static value ϵ_s at $f=0$, to about 20 at 40 GHz;[8] the parameter $\epsilon_\infty \approx 5$ and $\tau=8.27$ps, giving rise to a strong decrease in ϵ' in the microwave region of the electromagnetic spectrum, at about 20 GHz. Below 1 GHz, the decline of ϵ' is small; the difference $\epsilon_s - \epsilon'$ is 0.3% at 1 GHz. This difference, however, changes rapidly with the temperature, following the change in the relaxation time τ from 21.10 ps at 273.15 K to 4.01 ps at 333.15 K, and the change in the optical permittivity ϵ_∞ from 5.9 at 273.15 K to 4.2 at 333.15 K; $\epsilon_s - \epsilon'$ at 1 GHz ranges from 1% at 273.15 K to 0.06% at 333.15 K. In what follows, ϵ will denote the static dielectric constant.

This paper is ordered as follows. In Sec. 2, information is given about the organization of the data by region in phase space, the code used for the file names, and the transformation to the most recent temperature scale,[9] ITS–90. In Sec. 3, a brief review of the experimental methods is given and the likely sources of systematic errors are considered. In Secs. 4–7, the data sources are reviewed, including brief descriptions of the methodology, known sources of error, and corrections applied by us. The data are grouped according to region in thermodynamic phase space. Section 4 contains the data at the highest densities, in the region bounded by the normal freezing and boiling temperatures, at pressures from ambient up to the melting curves of ice V and VI. Section 5 contains the data in steam and water along the saturation curve. Section 6 covers the one-phase data above the normal boiling point and includes supercritical states. Section 7 contains the data at ambient pressure in metastable water below the normal freezing point. Section 8 present some concluding remarks. The appendix contains the tabulated original and corrected data sets. In addition, these are available on a diskette that can be obtained from AIP.[d]

2. Organization and Temperature Conversion of the Data

2.1. Grouping of the Data Sources.

Figure 1 displays 1,256 thermodynamic state points of water for which the dielectric constant has been measured, obtained from 36 articles from 1930 to the present. More than half of these measurements are in the high-density region bounded by the normal freezing and boiling temperatures, the isobar at ambient pressure, and the melting curves of ice V and VI, which we denote as Region A. The remaining points are located along the saturation curve (Region B), in the one-phase region above the normal boiling point (Region C), and in the range of supercooled water at ambient pressure (Region D).

The data sources have been grouped according to the above partitioning of the phase diagram, and the individual sources in each of the groups A-D are described in the corresponding Secs. 4–7, respectively.

2.2. Temperature Scale

All data have been converted to the International Temperature Scale of 1990, ITS–90, in a manner described below.

In 1927, the first international agreement about the temperature scale was reached by the introduction of the International Temperature Scale of 1927 (ITS–27).[10] Three revisions of the international temperature scale have been introduced since, namely the International Temperature Scale of 1948 (ITS–48),[11] the International Practical Temperature Scale of 1968 (IPTS–68),[12] and the International Temperature Scale of 1990 (ITS–90).[9] There is no difference between ITS–27 and ITS–48 in the temperature range of interest here. Unless the authors stated otherwise, we have assumed that all data published prior to February, 1969, the publication date of IPTS–68, had been obtained on ITS–48. The conversion from ITS–48 to IPTS–68 was accomplished by interpolation of the differences between the two scales published elsewhere.[13] The conversion from IPTS–68 to ITS–90 was carried out in accordance with Table 1.6 of the report "Supplementary Information for the ITS–90", of the Bureau International des Poids et des Mesures (BIPM), in the formulation published by Rusby.[14]

In the Appendix, and in the computerized data sets, we report all ITS-90 temperatures to three digits. This procedure in no way implies that the data have a smaller temperature uncertainty than that implied by the number of decimal places given in the original reports or publications. The procedure does guarantee that the original temperature is reproduced to 1 mK or better when the ITS-90 values are converted back to the original scale.

2.3. Organization and Nomenclature of Files

In this section we describe the nomenclature of the data files, and give details of the organization of the diskette containing the data base.

Two sets of data files have been prepared. Those contained in the directory called *ORIGINAL* correspond to those in the original publications, while the data contained in the directory called *CORRECTED* have been corrected by us. Corrections were made to bring data to a common temperature scale, as described in Sec. 2.2. In addition, individual data sets were further corrected as needed, by recalculating the pressure scale and the dielectric constant values determined from measurements relative to other fluids. Details of the corrections for individual data sets are given in Secs. 4–7.

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[d] See AIP Document No. PAPS JPCRD-24-33-disk for files of these data in machine-readable form. The data are available from AIP on disk as ASCII files, formatted by MS-DOS for IBM-compatible computers; the 88 files total 105 kB. When ordering, please indicate whether $3\frac{1}{2}$ inch or $5\frac{1}{4}$ inch disks are preferred.

Order by PAPS number and journal reference from American Institute of Physics, Physics Auxiliary Publication Service, Carolyn Gehlbach, 500 Sunnyside Blvd., Woodbury, NY 11797. The price is $10.00 in either format. Airmail additional. Make checks payable to American Institute of Physics.

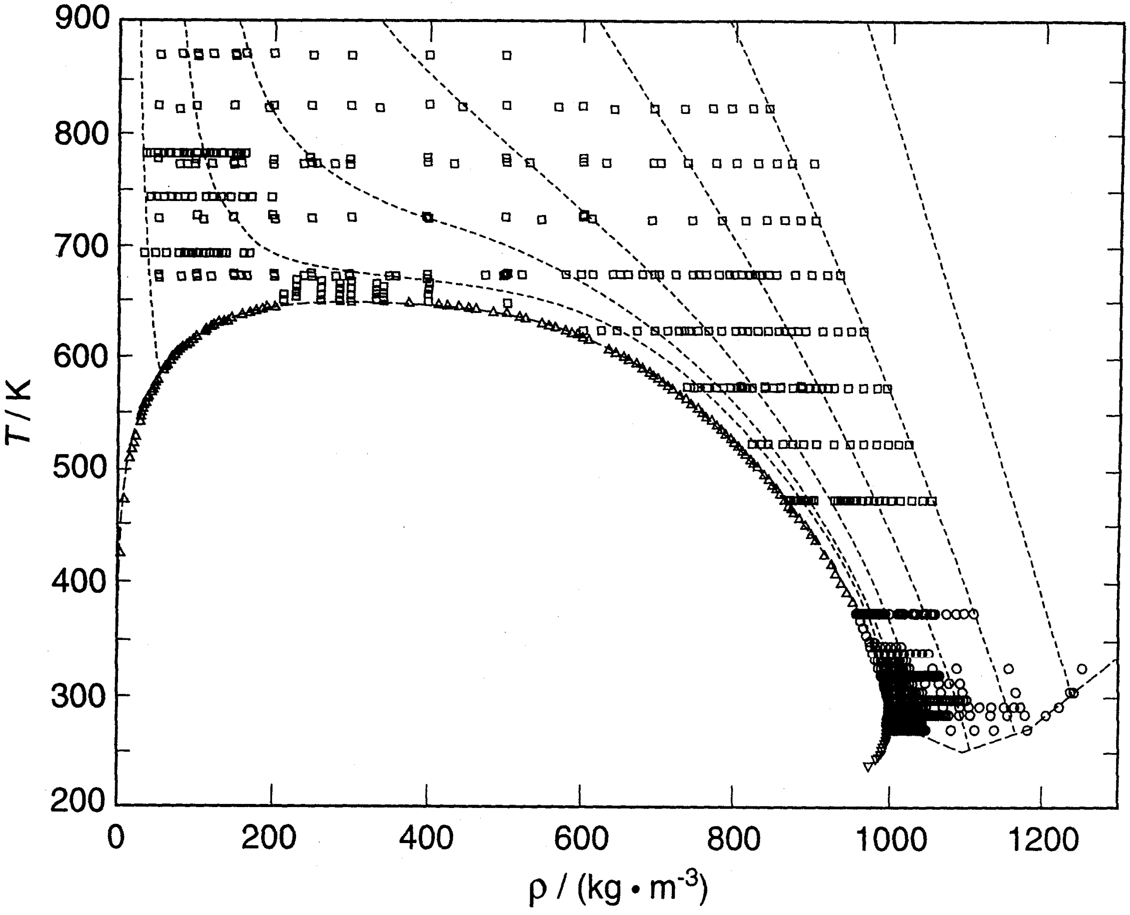

FIG. 1. State points at which the dielectric constant was measured. (○) Region A; (△) Region B; (□) Region C; (▽) Region D.

We adopted the following convention for the names of the individual data files. The first letter of the filename, A-D, refers to the region of thermodynamic phase space where the data were obtained, according to the convention defined in Sec. 2.1 and shown in Fig. 1. The next two numeric digits refer to the year when the results were published. They are followed by the first four letters of the surname of the first author. An additional alphabetic character appears if two different files would be assigned identical names in its absence. The files in the directory *ORIGINAL* have the extension *.or*. In the directory *CORRECTED* the files have an extension that defines some general characteristic of the data: *.at*, for data at ambient pressure; *.sv*, for data in the saturated vapor; *.sl*, for data in the saturated liquid. No extension is given if the data do not fall in one of these three categories.

Each data set is represented in a table by a single line (See Tables 1, 5-7). This line contains the number of the reference; the file name as defined above; the method and experimental ranges of variables; the reference substances used; the number of data points for the original and corrected files; and the experimental uncertainty as claimed by the authors.

3. Brief Review of Experimental Methods

As was mentioned in Sec. 1, the decline with frequency of the real part of the permittivity of water is small up to frequencies of 1 GHz. If an accuracy of 0.05% is desired for the static dielectric constant, as is the case for the best available measurements, frequencies below 100 MHz can be used with no further frequency-dependent correction for dipole reorientation at temperatures above 273.15 K. In the range below 1 GHz, two types of experimental techniques are used: in the low-frequency range, below 1 MHz, a cell filled with water can be treated as a capacitor in a circuit which imposes the frequencies of interest. For higher frequencies, when the wavelength is similar to the size of the sample, the geometry of the cell fixes the wave vector **k** and the frequency adapts according to the dielectric constant of the medium; a resonance frequency, rather than a capacitance, is then measured.

3.1. Low–Frequency Range: Lumped Circuits

Many different types of circuits were used in the determination of the dielectric constant of water up to frequencies of

30 MHz.[15] In the low frequency range, below 1 MHz, the capacitance and the dissipation factor of a three-terminal cell filled with water are generally obtained by a null method, involving some type of capacitance bridge (denoted CB in Tables 1, 5-7); in the older designs resistive ratio arms were used, while the more recent versions have inductive ratio arms. At frequencies above 1 MHz, the residual impedances of the lumped components introduce large errors in the bridge measurements. Resonant circuits (denoted RC in Tables 1, 5-7) are then preferred; in this case an inductor and a capacitor are loosely coupled to a generator, and resonance is indicated by a voltmeter; the capacitance of the cell filled with water is measured by a substitution method, and the loss component is determined from the width of the resonance curve g, usually at half-power. Finally, some experimenters have used an *LCR* meter, which is able to measure the inductive (L), capacitive (C) and resistive (R) components of the impedance of a sample over a wide range of frequencies.

The accuracy of the measurement of the capacitance of the cell filled with water in general deteriorates when the conductivity of the water rises; in this case, the large loss current in phase with the voltage, especially at low frequencies, implies a shallow minimum for the null method detection or a poor resonance peak (low quality factor $Q = f/2g$) for the resonant circuits.

The conductivity of pure water changes rapidly with temperature and pressure,[16] as can be seen in Fig. 2, for the saturated liquid phase. The largest errors for the capacitance of the cell due to this intrinsic conductivity are expected to occur close to 500 K for the liquid phase near the phase boundary. On the other hand, because of the difficulty of avoiding electrolytic contamination, many of the results reported in the literature were obtained with samples whose conductivity is more than ten times the value for pure water.

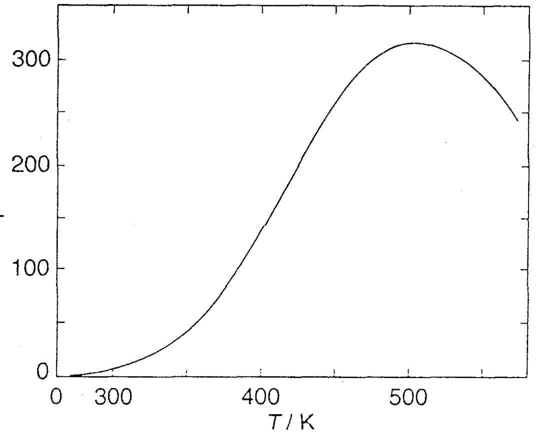

FIG. 2. Specific conductivity of liquid water along the saturation line.

Another related source of error is the residual capacitance associated with the resistance network used to balance the conductivity of the water. The capacitance of such a network, which is used to correct the capacitance of the cell filled with water, can be determined less accurately when a lower value of resistance is needed in order to compensate a sample with large conductivity.

Errors due to residual inductances of the circuit usually increase with frequency. This effect may give rise to an apparent frequency dependence of the capacitance of the cell filled with water; the correction required depends on the particular model circuit considered. The most common case found in the literature is an increase in the measured capacitance when the frequency increases.

In the low–frequency range, an increase of the capacitance with decrease of frequency is always noticeable. This effect is due to the presence of free ions, which can migrate in an electric field. At low frequencies, the ions have sufficient time to reach the surface of the electrodes in large numbers, and thus add an impedance to the system. For example, the proton has a mobility in water of about $4.10^{-7}\mathrm{m}^2\cdot\mathrm{s}^{-1}\cdot\mathrm{V}^{-1}$; consequently, the proton can migrate a distance larger than the size of a water molecule (0.2 nm) during half a cycle, at frequencies below 10 kHz and electric field strengths larger than 10^2 V·m^{-1}. Such condition are common in capacitance measurements with water. This phenomenon is called electrode polarization and has been studied extensively, but it is still not well understood.[17,18] The magnitude of the electrode polarization increases with the ionic concentration; at 298.15 K, even for the purest samples of water studied, the effect is noticeable at frequencies below 1 kHz.[19]

The capacitance finally obtained is, in most cases, a function of the frequency with a shallow minimum between 10 kHz and 50 kHz. Three examples from the literature are shown in Fig. 3; Fig. 3a corresponds to the function obtained by Malmberg and Maryott,[20] who used a capacitance bridge with resistive ratio arms; the experimental capacitances (open circles) were corrected by means of a model circuit with inductive elements (dashed curve). This correction only affected the capacitance values at the higher frequencies; at the lower frequencies, the increase of the capacitance was explained as the result of electrode polarization. Figure 3b shows the results of Vidulich and Kay,[19] who used a transformer bridge supplemented with an auxiliary conductance network. Figure 3c corresponds to the paper of Dunn and Stokes,[21] who used a circuit similar to that of Vidulich and Kay,[19] although at higher frequencies. Malmberg and Maryott[20], as well as Dunn and Stokes[21] used rather contaminated samples, with conductivities at least five times that of pure water. Vidulich and Kay,[19] instead, worked with water of higher purity, with a conductivity about 30% above the accepted value[16]; as a consequence, these authors found $(\partial C/\partial f)_T \approx 0$ between 5 kHz and 50 kHz.

In all the cases where electrode polarization is noticeable throughout the range of frequencies used, an extrapolation of the capacitance to infinite frequency is carried out. For the extrapolation, the data at each temperature T and pressure p are fitted to an empirical function of frequency of the form f^{-n}; the value for the exponent n ranges from 0.5 to 2 and in general is the same for all temperatures in any given experimental set–up. Once the capacitance value extrapolated to infinite frequency is calculated, it is then set equal to $C(T,p,\mathrm{H_2O})$, the capacitance of the cell filled with water at T

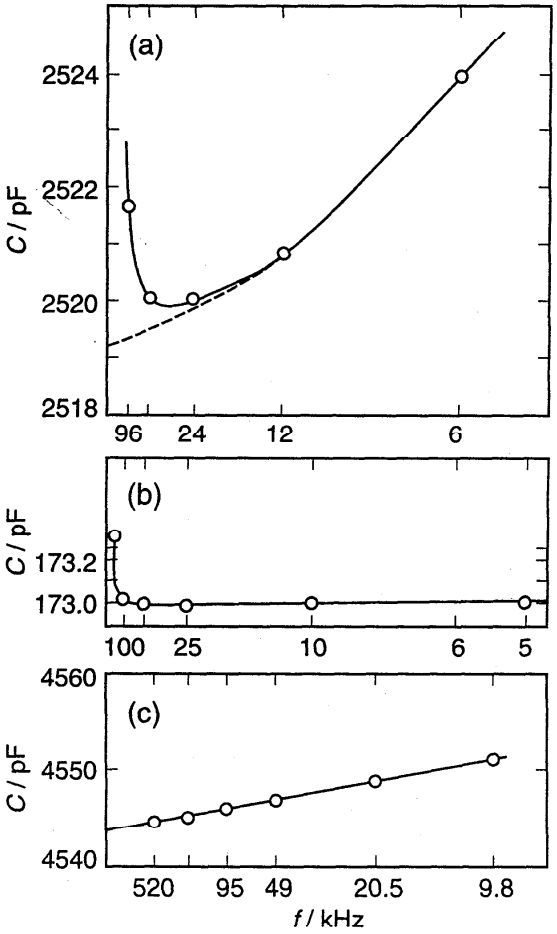

FIG. 3. Frequency dependence of the capacitance of the cell filled with water. (a) Malmberg and Maryott[20]; (b) Vidulich and Kay[19]; (c) Dunn and Stokes[21]. Note that the scale on the abscissa is linear in $1/f$ for (a) and (b), and linear in $1/f^{1/2}$ for (c).

and p, and the dielectric constant ϵ is obtained from the ratio

$$\epsilon = \epsilon_R \frac{C(T,p,\mathrm{H_2O})}{C(T,p,\mathrm{R})} \tag{4}$$

where $C(T,p,\mathrm{R})$ is the capacitance of the cell filled with the reference substance R, with dielectric constant ϵ_R. In general, the reference is vacuum, since the vacuum capacitance of the cell $C_v=C(T,p=0)$ depends only on its temperature, and $\epsilon_v=1$; C_v is measured at a reference temperature and $C(T,p,\text{vacuum})$ is then calculated from C_v considering the dimensional change of the cell with temperature and pressure; fractionally, these corrections are typically $1\cdot10^{-5}\ \mathrm{K}^{-1}$ and $2.5\cdot10^{-6}\ \mathrm{MPa}^{-1}$.

In general, in the cases where a resonant circuit is used to measure the capacitance of the cell filled with water, at frequencies of about 1 MHz, no study of the frequency dependence is made. The dielectric constant is reported at the experimental frequency.

3.2. High–Frequency Range

Microwave waveguide and transmission-line techniques have been widely used to study the complex permittivity of water between 1 GHz and 100 GHz.[6–8] Electromagnetic standing waves in coaxial lines[23–25] (denoted SW in Tables 1 and 5) and resonators of fixed geometry[26–28] (denoted R in Tables 1 and 5) are suitable for the study of the MHz band, in which the real part of the permittivity is within 0.3% of the static value (see Sec. 1).

The static dielectric constant is usually obtained by relating the resonance frequency of the coaxial line (or resonator) in vacuum, $f_v=f(T,p=0)$, and that when the line is filled with (or the resonator is immersed in) water, $f_w=f(T,p,\mathrm{H_2O})$:

$$\epsilon = \left(\frac{f_v}{f_w}\right)^2 \tag{5}$$

Equation (5) is an approximation based on a lumped-circuit analysis; it was used without further corrections in all the experiments in which the dielectric constant of water was measured by means of resonators,[26–28] and in the first coaxial–cavity experiment reported.[24] Owen *et al.*[25], on the other hand, corrected the resonance frequency observed in a coaxial line considering the loss attributed to the wall.

The observed resonance frequency in a coaxial line filled with a non-conducting fluid can be corrected according to

$$f' = \left(1 + \frac{1}{2Q}\right) f \tag{6}$$

where f' and f are, respectively, the corrected and observed resonance frequencies, and Q is the quality factor determined by the geometry and the permeability of the wall. If the imperfections in the geometry of the line are small, Q can be approximated by

$$Q = \frac{f}{2g} \tag{7}$$

where g is the difference between the measured frequencies at the maximum and at half power. The quality factor of the cell used by Owen *et al.*[25] was larger than 1000; for the coaxial line filled with water, however, the observed quality factor Q_w was less than 100, indicating a strong contribution of the fluid to the total loss.

The correction of the resonance frequency for the cell filled with water, due to the loss in the wall, can be achieved with Eq. (6), provided that an estimate for the quality factor reflecting the loss in the wall is available. The procedure used by Owen *et al.*[25] was to consider the ratio $Q/f^{1/2}$, known for the cell filled with nitrogen, independent of the cell content; the value for the quality factor for the cell filled with water due to the loss in the wall is now about 800. The value for the dielectric constant obtained with the corrected resonance frequencies, for the case of Owen *et al.*[25], is 0.1% less than the one obtained by using Eq. (5). We have made no attempt to improve on the models used by any of these authors.

TABLE 1: Region A

Ref.	File Name	T/K	p/MPa	Method[a](f/MHz)	Reference	No. of Data[b]	Uncertainty[g]/%
24	A30Drak	273–333	0.1	SW(1.3–8.6[c])	air	1	
26	A30Wyma	273–373	0.1	R(0.16–9.2[c])	air	7(6)	0.2
29	A32Aker	283–373	0.1	RC(2)	ref. 26	10	
30	A37Albr	291–323	0.1	CB(0.57)	air	4	
27	A38Wyma	273–373	0.1	R(48)	ref. 26	12[c]	
31	A39Tyss	293–298	0.1	RC(0.67)	chlorobenzene	14	
32	A46Albr	278–328	0.1	CB(0.57)	ref. 30	6	
33	A49Lees*	273–323	0.1–1,189	CB(0.01–1)	vacuum	38	0.01
34	A53Harr1	298	0.1–13	CB	ref. 46	3	0.5
35	A53Harr2	288–348	0.1–19	CB	ref. 27	24	
36	A55Miln*	273–298	0.1–101	SW(54[c])	vacuum	66	0.2
37	A55Scai	293	0.1–588	CB(1)	unspecified	10	< 4
23	A56Gran	273–333	0.1	SW(65–197[c])	unspecified	15(7)	0.6
20	A56Malm	273–372	0.1	CB(0.003–0.096)	vacuum	21	0.06
38	A58Coga*	298–343	0.1–101	SW(54[c])	vacuum	110	0.2
19,22	A62Vidu*	273–313	0.1	CB(0.0005–0.1)	vacuum	7	0.05
39	A66Rusc	273–298	0.1	CB(0.0005–0.05)	vacuum	45	0.035
40	A69Scha	293–318	0.1–126	CB(1.8)	ref. 27	39	0.01–0.05
41	A69Hege	373	0.1–500	CB(0.1)	vacuum	12	0.3
21	A69Dunn	278–338	0.1–207	CB(0.01–0.52)	ref. 20[e]	61	
42	A73Srin*	283–313	0.1–300	CB(0.002–0.02)	vacuum	21	< 0.03
7	A81Kaat	298	0.1	SW(100–114,000)	unspecified	1	0.05
43	A82Bert	274–305	0.1	RC(27.5)	ref. 20	7[f]	
44	A84Deul	298–373	0.1–300	LCR(0.01–1)	vacuum	48	0.2
45	A94Fern*	273–373	0.1	LCR-CB(0.0001–0.01)	vacuum	42	0.01–0.15

[a] SW=standing waves; R=resonator; CB=capacitance bridge; RC=resonant circuit; LCR=impedance meter.

[b] between parentheses is the number of points for the corrected database; otherwise the number of data for the original and corrected databases is the same.

[c] frequency at 298.15 K.

[d] obtained from an equation fitting 17 measured values (not reported).

[e] the vacuum capacitance was also calculated from the resistance of the capacitance cell filled with tetra-ethylammonium iodide in ethanol (see text for details).

[f] interpolated from a curve obtained with 80 experimental points (not reported) combined with results from Ref. 20.

[g] as given by the author(s).

*sets recommended for use in data correlations.

4. Region A: Liquid Water Below the Normal Boiling Point

In Table 1 we summarize the data sources for water between its normal freezing and boiling temperatures, at pressures exceeding the saturation pressure. The uncertainty listed in Table 1 is the estimate given by the author(s) in the published document. The comparison of the data from the different sources is organized in the next subsections. We begin with the review of all the papers which report absolute values for the dielectric constant of liquid water for this region; we then compare the atmospheric pressure data at T_0 and T_b; finally, the values for the temperature and pressure derivatives are compared. The file names identified with an asterisk in Table 1 represent the most consistent data sets in this region; these are the sources recommended to be used in data correlations.

4.1 Review of Relevant Papers

4.1.1. High-Frequency Measurements

The earliest values considered were obtained by Drake *et al.*[24] and by Wyman.[26] Drake *et al.*[24] measured the wavelength formed in a 3.7 m long brass pipe with a concentric copper wire, with distilled water filling the pipe. An oscillator was used to excite a resonance in air at frequencies between 11.8 MHz and 76.3 MHz. The half wave length within the dielectric was then obtained by means of a brass plunger, which had springs to make electrical contact between the pipe and the wire, and a calibrated ruler; by moving the plunger it was possible to determine the wavelength. In order to calculate the dielectric constant, Drake *et al.*[24] used the relationship

$$\epsilon=\left(\frac{f(T_0,p_0,\text{air})}{f(T,p_0,\text{H}_2\text{O})}\right)^2 \text{F}^2(h), \tag{8}$$

where f is the observed resonance frequency, T_0=298.144 K and p_0=0.101325 MPa. Here, $\text{F}(h)=[((1+h^2)^{1/2}+1)/2]^{1/2}$, with $h=2\kappa/f\epsilon$, where κ is the specific conductivity of the water. Although Drake *et al.*[24] included the conductivity of the water in this analysis, they found that the correction due to the conductivity was negligible for distilled water with a conductivity less than 1mS·m^{-1}.

Wyman[26] measured the resonance frequency of seven resonators, first in air and then entirely immersed in water. The resonators were metal spirals or cylinders with resonance frequencies in air between 1.4 MHz and 81.5 MHz. Each resonator was treated as a circuit composed of a lumped capacity C, inductance L and resistance R, arranged in series. The resonance frequency f at which the impedance of such circuit is a minimum, is given by

$$f = \frac{1}{(LC)^{1/2}}. \qquad (9)$$

Provided the magnetic permeability of the fluid is near unity and invariant, L is independent of the medium surrounding the resonator, therefore, the relation between the dielectric constant and the resonance frequencies in vacuum and water from Eq. (5) is readily obtained when Eq. (4) is used. Wyman[26] calculated the dielectric constant of water with a conductivity of 330 $\mu S \cdot m^{-1}$ in this way; he discussed the systematic error introduced by the conductivity of the water, and from analysis with Eq. (8), he concluded that Eq. (5) should provide results with an uncertainty less than 0.2% for frequencies above 1.3 MHz.

Resonance techniques were also used by Wyman and Ingalls,[27] Oshry,[28] Milner,[36] Cogan,[38] Grant *et al.*,[23] and Kaatze and Uhlendorf.[7] Wyman and Ingalls[27] used resonators to determine the static dielectric constant of water and deuterated water between the normal freezing and boiling points; the temperature dependence of the resonance frequency of the resonator in air was taken into account, improving the earlier measurements of Wyman.[26] Oshry[28] used resonators to determine the static dielectric constant of liquid water along the saturation line; his work will be discussed in Sec. 5.

Milner[36] and Cogan[38] were primarily interested in the pressure dependence of the static dielectric constant. They used essentially the same apparatus for determining the resonance frequency of a 31.2 cm gold-plated copper coaxial cavity filled with water at pressures up to 100 MPa. Milner[36] did not measure the vacuum resonance frequency of the cell, presenting only values for the dielectric constant relative to those of Wyman and Ingalls.[27] Later, Cogan[38] measured the resonance frequency of the cell filled with nitrogen at low pressure, and was thus able to calculate absolute values of the dielectric constant. The two studies were summarized in a later publication by Owen *et al.*,[25] in which a correlation for the dielectric constant and its temperature and pressure derivatives was presented; the average residual in the resonance frequency was less than 0.004%. Owen *et al.*[25] presumed that the difference of 0.2 % with respect to the value obtained by Malmberg and Maryott[20] at 273.15 K and atmospheric pressure was a consequence of Cogan's assumption regarding the quality factor, described Sec. 3.2. On the other hand, this assumption should have a much smaller effect upon the temperature and pressure derivatives of the dielectric constant, than on the absolute values. Cogan[38] presented a table of values of the dielectric constant at nominal values of temperature and pressure. This calculation involved smoothing by fitting the dielectric constant versus the temperature. Owen *et al.*,[25] on the other hand, produced an eight-parameter function that represented the resonance frequencies obtained by Milner[36] and Cogan.[38] For the present database, the 176 experimental frequencies obtained by these authors were transformed into dielectric constant values by correcting for the frequency as suggested by Cogan[38] and described in Sec. 3.2. For the 298.13 K and 308.12 K isotherms, Cogan[38] used a second cell, different from the one used by Milner[36] between 273.15 K and 298.14 K and by himself at other temperatures. The difference between the results at 298 K, the only temperature at which data were obtained with both cells, is about 0.15%. The second cell used by Cogan,[38] however, had a lower quality factor in vacuum than the first cell. In fact, the 298.13 K isotherm of Cogan[38] seems to have been disregarded in the representation developed later by Owen *et al.*,[25] in which only 165 experimental frequencies were considered.

Grant *et al.*[23] measured the temperature dependence of the complex permittivity in a coaxial-line cell using standing waves of 0.172 m and 0.520 m. These wavelengths correspond to frequencies of 576.5 MHz and 1.743 GHz in vacuum. As expected, the values obtained for the real part of the permittivity ϵ' at the higher frequency are lower than those obtained at 576.5 MHz; the maximum difference obtained is 3%, at 273.15 K. For the present data base, we considered only the values obtained at 576.5 MHz; this frequency corresponds to a resonance frequency in water of about 61.5 MHz at 273.15 K, given a static dielectric constant value close to 88. According to Eq. (2), with the values for ϵ_∞ and τ at 273.15 K given by Kaatze,[8] the difference between ϵ' at 61.5 MHz and the static value ϵ_s is fractionally less than $5 \cdot 10^{-5}$. For the same temperature and the higher frequency used, Eq. (2) predicts a value for ϵ' only 0.04% lower than ϵ_s, and therefore it is not possible to explain the 3% difference obtained by Grant *et al.*[23] between the values at the two frequencies used.

Kaatze and Uhlendorf[7] analyzed over 450 experimental values for the complex permittivity of water at temperatures between 269.05 K and 333.13 K, at atmospheric pressure, and in most of the cases at frequencies above 1 GHz. We have considered only one representative value for the present data base, which is shown in Table 2 for 298.14 K; this value corresponds to the parameter ϵ_s of Eq. (1), obtained when 103 experimental points for the complex permittivity at 298.15 K are fitted to Eq. (1). The lowest frequency considered is 100 MHz, and no static data from the literature were used in the fit. According to Eq. (2), at 298.14 K the difference between the real part of the permittivity ϵ' at 100 MHz and the static value ϵ_s is less than 0.01% if the values for ϵ_∞ and τ at 298.14 K given by Kaatze are used.[8] The value obtained by Kaatze and Uhlendorf[7] agrees very well with the other data shown in Table 2. For all the other temperatures considered in the paper of Kaatze and Uhlendorf,[7] the parameter ϵ_s from Eq. (1) was obtained from references 22 and 25, already included in the present data base.

4.1.2. Low-Frequency Measurements

In Refs. 19-22, 30, 31, 33, 39, 41, 42, 44, 45, and 47 the capacitance of a cell filled with water at frequencies less than 1 MHz was measured by means of a lumped circuit; the dielectric constant was then obtained from Eq. (4). The results of Malmberg and Maryott,[20] Rusche,[39] Vidulich *et al.*,[19,22] Srinivasan,[42] and Fernández *et al.*,[45] were obtained at frequencies below 100 kHz. All these authors found qualitatively similar behaviour of $C(T,p_o,f,H_2O)$ with frequency, with a shallow minimum between 5 kHz and 50 kHz.

TABLE 2. Dielectric constant of water at 298.14 K and 373.12 K at ambient pressure

			T/K			
			298.14		373.12	
Authors	Ref.	f/MHz	ϵ	$\kappa/\mu\mathrm{S{\cdot}m^{-1}}$	ϵ	$\kappa/\mu\mathrm{S{\cdot}m^{-1}}$
Drake, *et al.*	24	1.3–8.6	78.61	1,000		
Wyman	26	0.16–9.2	78.58	330		
Wyman and Ingalls	27	48			55.93	
Oshry	28	58–113			55.56	
Milner	36	54	78.36	150		
Grant, *et al.*	23	65–197	78.43			
Kaatze and Uhlendorf	7	100–40,000	78.32	200		
		f/kHz				
Albright	30	570	78.52			
Tyssul Jones and Davis	31	670	78.53			
Lees	33	10–1,000	78.39	160		
Malmberg and Maryott	20	3–96	78.30	50	55.65	170
Vidulich, *et al.*	19,22	0.5–100	78.39	7		
Rushe	39	0.5–50	78.46	15		
Heger	41	100			55.30	<10,000
Dunn and Stokes	21	10–520	78.30	>80		
Srinivasan	42	2–20	78.45	10		
Lukashov	47	5–25			55.55	<480
Deul	44	10–1,000	78.36	80–2000	55.31	<4,000
Fernández, *et al.*	45	0.1–20	78.40_6	5.7	55.58	84
		average	78.43		55.55	
		standard deviation	0.10		0.21	

The measurements of Malmberg and Maryott[20] were carried out in a three-electrode capacitance cell formed from tin-coated copper plates, silver-plated copper spacers, pyrex glass rings and bakelite bushings. The assembled cell was not entirely immersed in the thermostat, but the exposed portion was insulated. The water was boiled in the cell in order to eliminate dissolved air, and the sample was thereafter maintained under a hydrogen atmosphere. The capacitance of the cell was obtained by means of a ratio-arm bridge. The three-electrode cell was connected to the bridge with a "Wagner ground", thereby allowing two- and three-terminal measurements. A Wagner ground allows the balancing of the bridge with the detector to ground, thus eliminating the effect of detector capacitance to ground.

In order to analyze the different errors, the cell was modelled as a capacitor in parallel with a resistor, and these two in series with an inductor and resistor corresponding to the leads. The difference between the inductance of the leads and that of the measuring arm determined a maximum correction of 0.1% at the higher frequencies, this being the most important correction presented by Malmberg and Maryott[20]. This correction is represented as a dashed line in Fig. 3a. The corrected values of capacitance C were then extrapolated to infinite frequency using the function $C = C_\infty + a/f^b$, where a and b are constants for a given experiment and temperature.

Malmberg and Maryott report their data at the experimental temperatures in their Table 2, as values calculated from a polynomial in temperature, their Eq. (5), fitted to the measured data. They also report in their Table 2 the departures of the experimental data from the fitted curve. We regenerated the experimental data by subtracting the departures from the calculated values. We were not able to reproduce the calculated values in their Table 2 by using their Eq. (5). In the only case where an experimental value had been reported, that at 298 K in their Table 1, our adopted procedure reproduces the experimental data point, but their Eq. (5) does not. We therefore concluded that Eq. (5) was reported incorrectly.

Vidulich *et al.*[19,22] used a high-purity sample in a cell formed from three platinum electrodes painted on pyrex glass. Using a ratio transformer bridge, which eliminates all errors due to capacitance to ground, supplemented with an auxiliary conductance network they were able to study the frequency dependence of the capacitance of the cell filled with water. As shown in Fig. 3b, these authors found a shallow, almost undetectable minimum in C at about 20 kHz, with a rapid increase at frequencies larger than 100 kHz. At frequencies less than 20 kHz, where the electrode polarization dominates the behaviour of the capacitance with the frequency, the curve obtained by Vidulich *et al.*[19,22] is rather flat; the value for $(1/C)(\partial C/\partial f)_{T_0}$ in this frequency range, $2\cdot 10^{-5}$, is one order of magnitude less than the one shown by Malmberg and Maryott.[20] This we attribute to the low specific conductance of the water used by Vidulich *et al.*[19,22] which was a factor of ten less than that of Malmberg and Maryott.[20] Vidulich *et al.*[22] found that $C(T,p_0,f\to\infty,\mathrm{H_2O})$ depended strongly on the conductivity of the water, which they associated with the variations of the capacitance arising from the resistance network used in their circuit. The extrapolated values for different conductivities collapsed to a common value if an effective capacitance of $-2.5\cdot10^{-3}\,p$F was attributed to the resistance network.

Rusche[39] used a cell similar to the one used by Vidulich *et al.*[19,22] and measured the dielectric constant of supercooled and liquid water from 268.3 K to 298.2 K. The original values obtained by Rusche[39] were corrected by us, always by less than 0.08%, according to the criticism of Kay *et al.*[49] These authors estimated the correction due to the capacitance associated with the resistance network used by Rusche[39] to balance the conductivity of the water. This resistance network happened to be similar to that used by Vidulich and Kay[19] in an earlier work; the correction is less than 0.08%.

Srinivasan[42] used a high-pressure version of the cell used by Vidulich, *et al.*[22] and described above. The capacitor, with a shrinkable sleeve attached to it and placed inside a pressure vessel, was connected to a ratio-transformer bridge provided with a resistance network. The water used was carefully purified, the conductivity being only twice that of pure water. The frequency dependence obtained was linear between 2 kHz and 20 kHz. The difference between the capacitance measured at 8 kHz and the value extrapolated to infinite frequency was never greater than 0.03%.

Fernández *et al.*[45] reported measurements of the dielectric constant of liquid water in the temperature range from the normal freezing to the normal boiling point, obtained from the capacitance of a cell assembled from stainless-steel concentric cylindrical electrodes and sapphire insulators. They used two different types of capacitance measurement devices; one of these was an automatic transformer bridge, the other an *LCR* meter. Special care was taken to purify the water; carbon dioxide was removed by bubbling through nitrogen gas, and, by means of a pump and a water purifier, a recirculating system was set up that maintained the conductance of the water in the cell within 20% of the value for pure water at each temperature. The capacitance of the cell filled with water was corrected at each temperature and frequency by means of a substitution method, with an equivalent circuit formed by a capacitor and a resistor in parallel.

The corrected values of the capacitance were then extrapolated to infinite frequency. The values obtained with the transformer bridge above 343 K had a higher uncertainty than those obtained with the *LCR* meter, due to better reproducibility and smaller corrections for this last instrument. Fernández *et al.*[45] studied the effect of the purity of the water on the capacitance: they found that the value extrapolated to infinite frequency decreases when the conductivity of the water increases, both at T_o and T_b.

Lees,[33] and Dunn and Stokes,[21] used frequencies above 100 kHz. Dunn and Stokes[21] used a cell assembled from two cylindrical platinum electrodes coated with platinum black and placed inside a pyrex vessel. The cell was calibrated by means of two independent methods. First, the vacuum capacitance was calculated from the measured capacitance when the cell was filled with water at T_o=298.14 K, where $\epsilon(T_o,p_o,H_2O)$=78.30 was assumed, as reported by Malmberg and Maryott.[20] Second, the conductivity of a solution of tetraethyl ammonium iodide in ethanol was determined both in the capacitor and in a previously calibrated conductance cell. From these measurements, it is possible to calculate the constant K_c of the capacitor when it is used as a conductance cell; the vacuum capacitance of the cell is then calculated with the relationship $C(T_o,p{=}0)=\epsilon_o/K_c$, where ϵ_o is the vacuum permittivity. These two methods yielded vacuum capacitance values that differed fractionally by less then $2.5\cdot10^{-4}$. The capacitance of the cell filled with water, when determined with a transformer bridge, shows no increase at frequencies up to 520 kHz. This is inconsistent with other observations: as discussed above, other authors report an increase of the capacitance above a certain frequency, in the range from 50 kHz to 5 kHz. As seen in Fig. 3c, the capacitance obtained by Dunn and Stokes[21] plotted as a function of $f^{-1/2}$ yields a straight line that can be easily extrapolated to infinite frequency. The extrapolated value was found to be independent of the conductivity of water even at resistances as low as a few ohms.

The thesis of Lees[33] constitutes the first accurate work studying the dielectric constant of liquid water at very high pressure. The highest-pressure states studied, for pressures greater than 1 GPa, can be easily distinguished in Fig. 1 close to the freezing curve of ice IV; no other experimental work has explored this region. An ac bridge operating at frequencies of 10 kHz, 100 kHz and 1 MHz was used to measure the capacitance of the cell. The capacitor, inserted into a tin-foil bag which served as a pressure transmitter, was assembled from gold-plated copper cylinders and silica insulators. The vacuum capacitance changed by less than 0.3% after pressure excursions up to 1 GPa. Hysteresis phenomena were carefully quantified and corrections applied. Lees[33] used the freezing pressure of mercury at 273.15 K to calibrate the pressure gage. The currently accepted value for this reference pressure[50] is 1% higher than the value used by Lees.[33] Therefore, we have corrected the pressures listed in the original thesis by the ratio of the currently accepted value to that used by Lees.[33] The pressure cell was calibrated by measuring the dielectric constant of water at atmospheric pressure and 296.536 K with a variable capacitor; the reproducibility of this calibration was, according to Lees[33], better than 5 parts in 10^{-6}. The capacitance observed at each frequency was corrected for electrode polarization, the corrections not exceeding 0.03%, and the dielectric constant was calculated from this corrected value at 10 kHz, 100 kHz and 1 MHz. The final result for the dielectric constant of water was presented at the frequency of 100 kHz. The results at 1 MHz, however, differed from the results at 100 kHz by as much as 0.06%; this difference was independent of the conductivity of the water samples used. As a consequence, a low-frequency dispersion characteristic of water was postulated. No other experimenters have reported this effect.

4.2. Values of $\epsilon(p{=}0.1\text{ MPa})$ at T_o and T_b

Table 2 lists the dielectric constant of water at 298.14 and 373.12 K, at p_o=0.101325 MPa. The values were obtained from the references, shown in Table 1, that provide ambient pressure data near T_o and T_b, either relative to vacuum, or to any substance for which the dielectric constant is well known. The papers by Oshry[28], Heger[41] and Deul[44], and the thesis by

Lukashov[47], will be discussed in Secs. 5 and 6, since these authors were mainly interested in temperatures above T_b.

Original data for ϵ from Refs. 24, 26, 27, 29, 30, 32, 35 and 40 are relative to air or other measurement relative to air. Since no correction was reported, we corrected these data according to

$$\epsilon = \epsilon_{air}\epsilon_{r,air} \tag{10}$$

where $\epsilon_{r,air}$ is the value relative to air and ϵ_{air}=1.00054.[48] The value at 298.15 K from Ref. 27 was not included in Table 2 since it had been taken from Ref. 26. The correction to nominal values of temperature is insignificant in all cases, given the uncertainty of the measurements.

Table 2 is divided in two sections, according to the frequency range used in the experiment. In the upper part, values for the dielectric constant obtained mostly at frequencies greater than 1 MHz (Sec. 4.1.1.) are shown, while in the lower portion the data refer to $f \leq 1$ MHz (Sec. 4.1.2.). The papers are listed chronologically in both cases.

Figure 4a shows the differences with respect to the average of all the values of the dielectric constant at T_o listed in Table 2, as a function of the maximum frequency used, for the low frequency methods; or as a function of the minimum frequency used, for the high frequency methods. No clear trend with frequency is observed in Fig. 4a. For data from authors who claimed accuracies better than 0.1% (Refs. 20, 22, 33, 39, 42, 45) the average value of the dielectric constant at T_o is 78.40. This value is lower than the mean of all the values listed in Table 2, 78.43. The difference of 0.03 suggests that the data of Refs. 24, 26, 30, and 31, which are the highest values listed in Table 2, could be in error; these references correspond to the oldest works quoted and no corrections were applied to the experimental results before calculating ϵ with Eq. (4) or with Eq. (5).

Figure 4b shows the difference of the data reported in Refs. 20, 21, 22, 33, 39, 42, 44, and 45, from the mean of this set, 78.38, as a function of the conductivity of the water used to perform the measurement. The data considered are those obtained by methods in the range up to 1 MHz , with the exception of the data reported by Refs. 30 and 31. There seems to be some indication that the impurities in the water tend to render lower values for the dielectric constant. The dielectric constant reported by Malmberg and Maryott,[20] and by Dunn and Stokes,[21] are the lowest values shown in Fig. 4b. These two groups of experimenters obtained the same value at T_o, with similar corrections due to electrode polarization. The values of capacitance extrapolated to infinite frequency as obtained by Malmberg and Maryott,[20] and by Dunn and Stokes,[21] differed by 0.09% and 0.15%, respectively, from the capacitances observed at 10 kHz. Vidulich *et al.*[19,22], Srinivasan,[42] and Fernández *et al.*,[45] due in part to the higher purity of the water used, found that the capacitance changed very little as a function of the reciprocal frequency for the major part of the frequency range; the difference between the extrapolated value and the capacitance at 10 kHz was in these cases less than 0.01%.

If the values obtained by Malmberg and Maryott[20] and Dunn and Stokes[21] are disregarded, in addition to those of Refs. 24, 26, 30 and 31, the average obtained from Refs. 7, 22, 23, 33, 36, 39, 42, 44 and 45 is 78.40. This value also agrees with the average of the data with claimed uncertainties less than 0.1%. One standard deviation for the average of these data equals 0.05. We propose ϵ=78.40±0.01 as the best estimate at T_o, with the uncertainty representing two standard deviations of the data with the highest water purity, those of Fernández *et al.*[45]

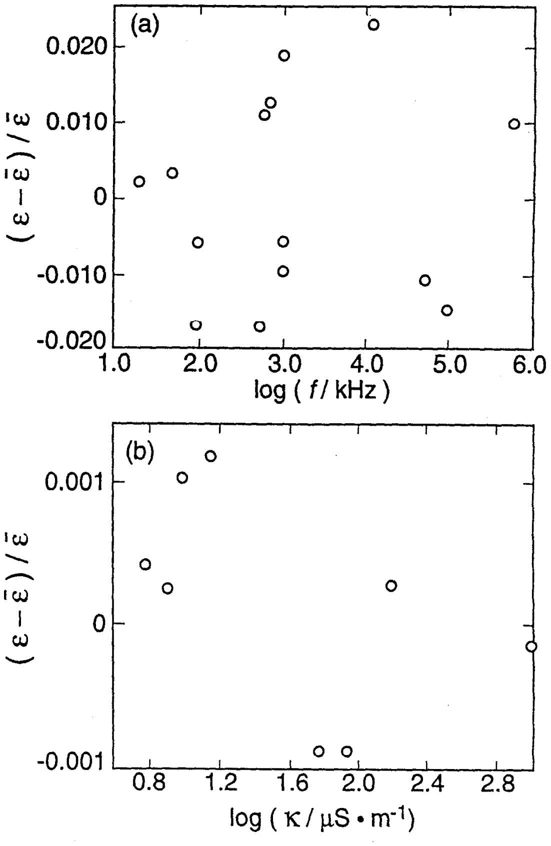

FIG. 4. Comparison of experimental data for the dielectric constant of water at 298.15 K and ambient pressure. (a) as a function of frequency used; (b) as a function of specific conductivity of the water for low–frequency experiments (See Table 2).

At T_b the data shown in Table 2 present a higher standard deviation of the mean as compared with the one obtained from the data at T_o. The value obtained by Wyman and Ingalls[27] is the highest shown; this value is relative to the value obtained by Wyman[26] at T_o , which was found to be high according to the discussion above. Oshry[28] was interested in the saturated liquid phase and his thesis will be discussed in Sec. 5. The result at T_b shown for Oshry[28] was calculated from an analysis provided by him. The values of Heger[41] and of Deul[44] are the lowest observed. In both cases the conductivity of the water

TABLE 3. Temperature dependence of the dielectric constant of water at p_o=0.101325 MPa

Authors	Ref.	$-(\partial\epsilon/\partial T)_{p_o}/\mathrm{K}^{-1}$	
		298.14 K	373.12 K
Åkerlöf	29	0.368	0.262
Albright	30	0.369	
Wyman and Ingalls	27	0.360	0.257
Albright and Gosting	32	0.366	
Oshry	28		0.245
Lees	33	0.360	
Harris, *et al.*	35	0.361	
Milner	36	0.358	
Grant, *et al.*	23	0.369	
Malmberg and Maryott	20	0.356	0.254
Rusche	39	0.357	
Vidulich, *et al.*	22	0.360	
Dunn and Stokes	21	0.356	
Lukashov	47		0.264
Fernandez, *et al.*	45	0.359	0.258
	average	0.361	0.257
	standard deviation	0.005	0.007

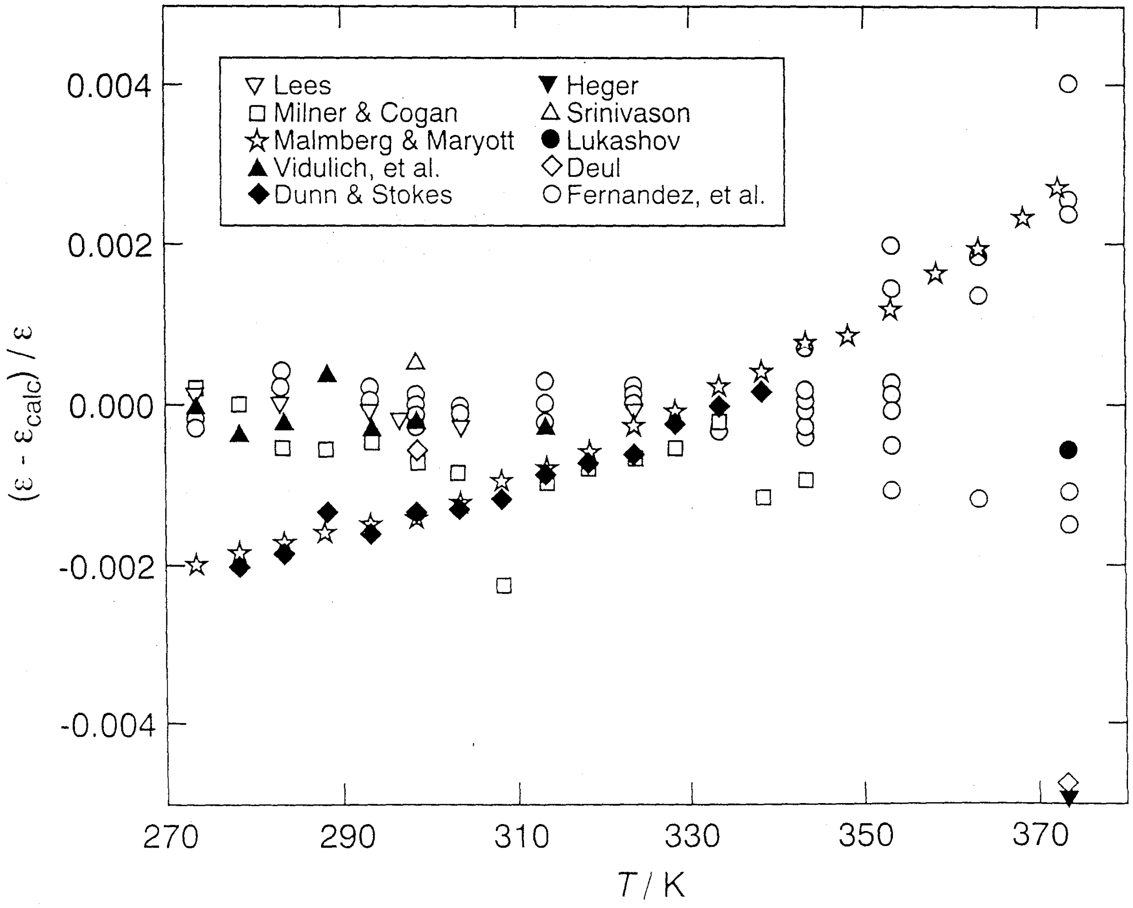

FIG. 5. Comparison of experimental data for the dielectric constant of water at ambient pressure between 273.15 K and 373.15 K.

TABLE 4. Pressure dependence of the dielectric constant of water

		$10^4\cdot(\partial\epsilon/\partial p)_T$/MPa^{-1}												
	T/K	273.15	283.14		293.14		298.14			303.13	318.13	338.12	373.12	
	p/MPa	50	50	200	50	400	10	50	200	50	50	50	50	100
Authors	Ref.													
Lees	33	388	366	325	350	268				337				
Milner	36	388	370		353		369	348						
Scaife	37				379	296								
Cogan	38						366	349		346	329	313		
Schadow and Steiner	40				366					374	274			
Heger	41												284	232
Dunn and Stokes	21		368	323			357	344	299		330	311		
Srinivasan	42		362	308			353	343	305					
Deul	44						377	356	278				327	237
average		388	367	319	362	282	364	348	294	352	311	312	306	235
standard deviation		0	3	9	13	20	10	5	14	19	32	1	30	4

used was at least fifty times the value reported for pure water, 76.5μS·m^{-1}, and no frequency correction was applied. The measurements of Heger[41] and of Lukashov[47] were mainly devoted to the high temperature region, while Deul[44] was interested in the dielectric constant of mixtures of benzene and water at high temperatures. These three works will be discussed in more detail in Secs. 5 and 6. The value of ϵ=55.65 reported at T_b by Malmberg and Maryott[20] lies above the average, opposite to the trend found at T_0. We propose ϵ=55.56±0.06 as the best value at T_b; this corresponds to the mean obtained from Refs. 28, 45 and 47. The uncertainty is again that of Ref. 45.

4.3. Temperature Dependence at Atmospheric Pressure

Table 3 shows values of $-(\partial\epsilon/\partial T)_{p_0}$, at T_0 and T_b. The only data sets considered were those with more than five points. The data in each set were represented by a third–order polynomial in temperature, from which derivatives were calculated at nominal temperatures within the experimental range.

The data obtained by Åkerlöf,[29] and by Albright[30] at T_0, are 2.5% higher than the average. The data from Refs. 22, 27, 33, 35, 36, and 45 at T_0 are in close agreement, with an average of 0.360 K^{-1} and a standard deviation less than 0.3%. The data obtained by Malmberg and Maryott[20], and by Dunn and Stokes[21] at T_0 are the lowest shown; they are 1.4% less than the average. At T_b, the value obtained from the analysis of Oshry[28] is 5% below the average. The data from Refs. 20, 27, 29, 45 and 47 provide an average of 0.259 K^{-1}, with a standard deviation of 1.5%.

Figure 5 shows the residuals obtained when the ϵ data between T_f and T_b of Refs. 22, 28, 33, 36, 38, 42, 45, and 47 are fitted with a third order polynomial in T. Only the data of higher accuracy above 343 K of Ref. 45, those obtained with the *LCR* meter, were considered in the fit. The point at 308.15 K, that of Cogan[38], is a result obtained with a cell of lower quality factor and was not included in the fit. The data of Malmberg and Maryott[20] and of Dunn and Stokes[21] deviate systematically from the empirical expression.

4.4. Pressure Dependence Between the Normal Freezing and Boiling Points

Table 4 presents a comparison of the values of the pressure derivative $(\partial\epsilon/\partial p)_T$ obtained from the different sets of data. Each experimental isotherm, with the exception of those obtained by Lees,[33] was fitted by means of a third–degree polynomial in the pressure, and the derivatives were calculated at nominal temperatures and pressures. No significant error was introduced by neglecting the difference between the experimental and nominal temperature. A fourth-degree polynomial in the pressure was necessary in order to fit the isotherms obtained by Lees,[33] with a pressure range of over 1 GPa.

Figure 6 represents the comparison for some of the isotherms. In Fig. 6a, the residuals of ϵ at T_0 for the data of Refs. 21, 36, 38, 42 and 44 are represented as a function of pressure; a third–order polynomial in pressure was fitted to the data of Milner,[36] Srinivasan[42] and Deul[44], with equal

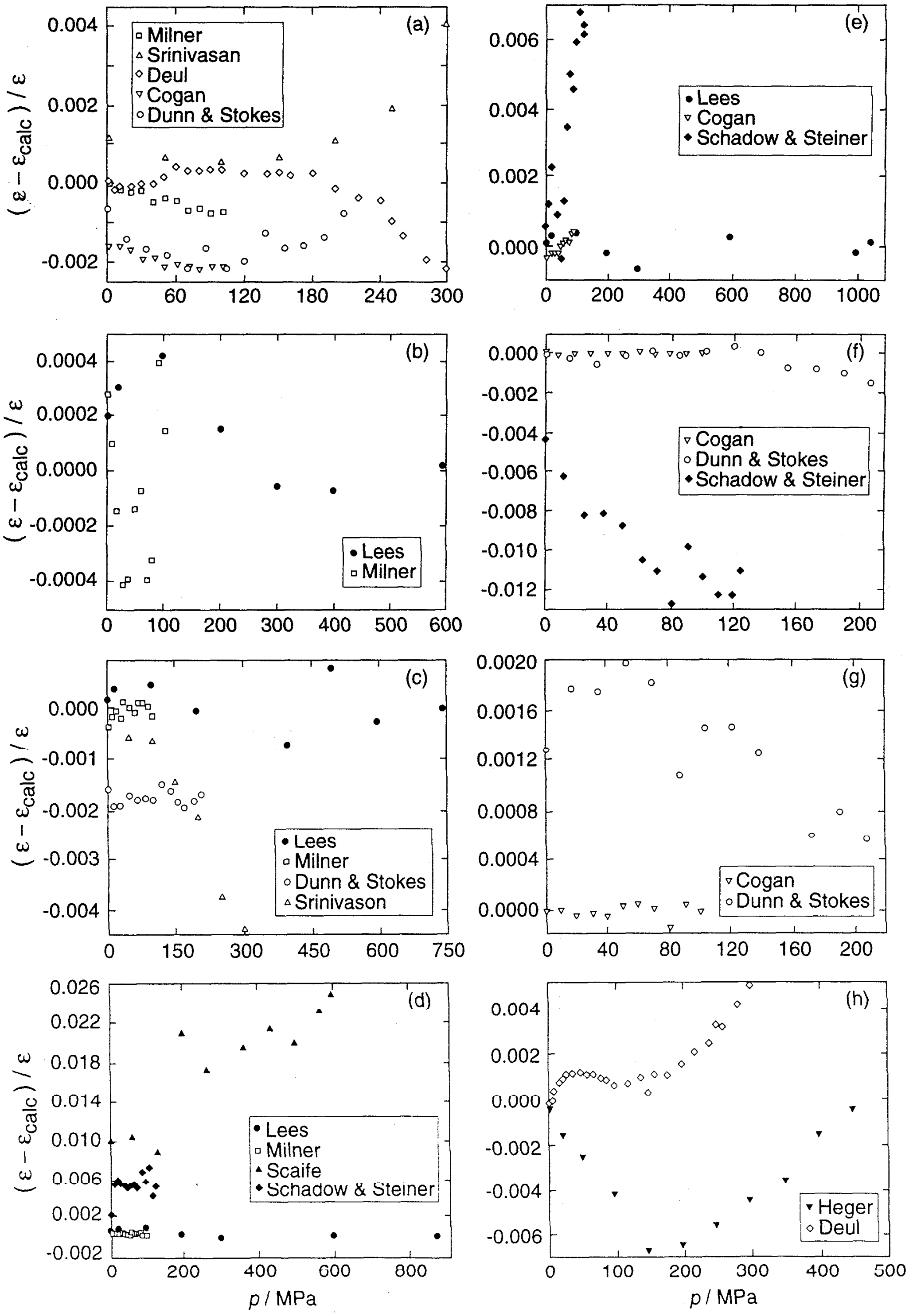

FIG. 6. Comparison of isothermal experimental data for the dielectric constant of water between 273.15 K and 373.15 K, and pressures up to 750 MPa. T in K: (a) 298.14; (b) 273.15; (c) 283.14; (d) 293.14; (e) 303.13; (f) 318.13; (g) 338.12; (h) 373.12.

weights assigned to each set. The results obtained by Cogan[38] with the same method as Milner's,[36] but with a second cell of lower quality factor, are 0.15% lower than the average. The results from Dunn and Stokes[21] are also low, by the same amount as the results at ambient pressure, that are compared in Fig. 5. The agreement in $(\partial\epsilon/\partial p)_T$ at T_0 is better than 3% in the low–pressure range and deteriorates above 150 MPa; at 200 MPa, the pressure derivatives obtained from the data of Srinivàsan[42] and Deul[44] differ by up to 9%. Figure 6b compares the data obtained by Lees[33] and by Milner[36] at T_f. The values of ϵ agree within 0.05%, and the pressure derivatives at 50 MPa differ by less than 0.2%. At 283.15 K, the comparison shown in Fig. 6c, which is based on a fit to the data from Lees[33] and from Milner[36] is similar to that at T_o, shown in Fig. 6a: the data obtained by Lees[33] and by Milner[36], agree within 0.05%; the data from Dunn and Stokes[21] are about 0.2% lower than the average; and the data from Srinivasan[42] agree very well with the average in the lower pressure range, but deviate systematically at pressures larger than 100 MPa. At 200 MPa and 283.15 K, the value for $(\partial\epsilon/\partial p)_T$ obtained from the data of Srinivasan[42] is 6% lower than that the value obtained from the data of Lees.[33] Figures 6d, 6e and 6f show systematic deviations with respect to the average for the data obtained by Scaife[37] at 293.14 K and by Schadow and Steiner[40] at 293.14 K, 303.13 K and 318.13 K. The agreement between the data from Lees[33] and Milner[36] at 293.14 K, obtained by Lees[33] and Cogan[38] at 303.13 K, and by Cogan[38] and Dunn and Stokes[21] at 318.13 K, is as good as the best obtained for this region, within 0.05%. At 338.12 K, the data from Dunn and Stokes[21] and Cogan[38] are compared in Fig. 6g; the dielectric constant values obtained by Dunn and Stokes[21] are about 0.2% higher than the values obtained by Cogan[38]; the pressure derivatives at 50 MPa agree to better than 1%. Finally, Fig. 6h shows the comparison at 373.12 K, where only two sets of data are available: those of Heger[41] and Deul.[44] The dielectric constant data agree better than 1%; the pressure derivatives differ by 15% at the lower pressures, although the agreement improves at pressures greater than 150 MPa.

5. Region B: Saturation Line

Table 5 summarizes the results of five experiments performed along the phase boundary. The file names identified with an asterisk represent the most consistent data.

Following the method proposed by Wyman,[26] Oshry[28] measured the resonance frequency of four platinum resonators immersed in liquid water close to saturation, from the boiling to the critical point. The resonators were placed inside a stainless steel pressure vessel and the resonance frequency was measured by comparison with a vacuum tube oscillator. The resonance frequencies in air ranged between 430 MHz and 840 MHz, and changed by only 0.4% in the whole temperature range of 373 K to 654 K; no correction for pressure was considered. Corrosion of the steel was observed when the cell was filled with water, although no difference in the resonance frequency was found for fresh samples of water as compared to samples used repeatedly. The values for the dielectric constant were obtained using Eq. (5). Oshry presented 123 experimental points, seven of which are at supercritical temperatures. At subcritical temperatures, the pressure was maintained slightly above the saturation pressure, and it was measured with an accuracy of 0.004 MPa. Unfortunately, those pressure values were not given, and neither was the source for the saturation values. Using the data obtained by Wyman and Ingalls,[27] Oshry determined a five-parameter temperature dependent function that follows the variation of the dielectric constant between 273 K and 640 K, with a value of 9.05 predicted for the critical point. Above 600 K, however, the scatter from this function was about 11%.

Fogo *et al.*[54] measured the dielectric constant of water along several isochores in the critical region, see Fig. 1, right above the dome of the coexistence curve. These data will be presented in the next section, according to the partition outlined in Sec. 2.1. We estimate, based on the values reported by Fogo *et al.*, that the value ϵ at the critical point equals 5.4.

The remaining studies represented in Table 5 were carried out in the former Union of Soviet Socialist Republics. At the

TABLE 5. Region B

Ref.	File Name	T/K	Phase	Method[a](f/MHz)	Reference	No. of Data[b]	Uncertainty[e]/%
28	B49Oshr*	372–654	liquid	R(58–113)	vacuum	123(116)[b]	1–10[c]
51	B75Svis	529–641	vapor	CB(0.02)	vacuum[d]	39	2
47	B81Luka*	373–643	liquid	CB(0.015–0.02)	vacuum[d]	10	0.8
47	B81Luka	423–643	vapor	CB(0.015–0.02)	vacuum[d]	19(18)	0.8
52	B88Much	473–633	vapor	CB(0.05)	vacuum[d]	7	0.7
53	B94Mule*	510–614	vapor	CB(0.05–0.1)	vacuum[d]	25	0.15

[a] R=resonator; CB=capacitance bridge.

[b] between parentheses is the number of points for the corrected data file.

[c] scatter of the points.

[d] the vacuum capacitance was calculated from the dimensions of the capacitor.

[e] as given by the author(s).

*set recommended for use in data correlations.

Rostov Civil Engineering Institute, Lukashov[47] investigated the static dielectric constant of water at temperatures up to 873 K, using a platinum capacitor with a guard ring inside a platinum-lined autoclave. He performed measurements along the saturation line, for both liquid water and steam, and in the one-phase region. The data published in his Doctoral dissertation superseded earlier results published in Teploenergetika.[55] A later publication in the same journal, Ref. 56, presents a correlation of the data obtained in his thesis. Lukashov and Shcherbakov[56] provided an estimate for the dielectric constant at the critical point of 5.38, which is in good agreement with the value obtained from the data of Fogo *et al.*[54] Pressure and temperature were the experimental variables; the densities were calculated in an unspecified fashion, on the basis of the (p, V_m, T) data of Rivkin.[57] The pressures were not given, only temperature and density were reported. In the corrected database, we list the densities as reported in the doctoral dissertation of Lukashov[47]. Because the data appeared to have been taken at integer temperature values on the Celsius scale, we added .15 K to the absolute temperatures appearing in the thesis, although these were mostly reported without decimals. The change in ϵ due to this change in temperature, of 0.15 K, is insignificant when we consider the experimental uncertainty of ϵ and the value of $(\partial\epsilon/\partial T)_p$ obtained from the smoothed data reported by Archer and Wang.[5]

The three other experiments listed in Table 5, carried out at the vapor (steam) side of the coexistence curve, were performed at the Moscow Power Institute. The data of Svistunov[51] were published in the Doctor's dissertation of Golubev,[58] and, in graphical form only, in Teploenergetika.[59] The data of Muchailov[52] and Mulev[53] were published in their respective Candidate's Dissertations. The data previously obtained by Svistunov[60] and other data[61] published in graphical form were not considered for the present database.

Svistunov[51] used a parallell-plate capacitor with a guard ring. This permitted him to calculate the vacuum capacitance from geometrical dimensions, assuming that the guard ring was perfect (which is seldom the case). Muchailov[52] and Mulev[53] used stainless-steel cylindrical capacitors with a guard ring and ceramic insulators. The vacuum capacitance was obtained by calibration with liquids of known dielectric constant, and from the dimensions of the cells.

In Fig. 7 we compare the values reported along the saturation curve. For both saturated gas and liquid, we found that the data can be conveniently represented as a function of the scaled variable ρ/T. The data for steam were fitted to a second-degree polynomial in ρ/T with the constraint $\epsilon=1$ for $\rho/T=0$. Figure 7a shows the residuals from the fit for steam. In general, the data agree within 3%. The scatter for the data of Mulev,[53] however, is less than 0.5%. The data of Muchailov[52] seem to deviate systematically from the average at the higher densities. For the liquid phase, shown in Fig. 7b, five coefficients were used to fit the data of Oshry[28] and Lukashov.[47] The agreement is better than 1% for the higher densities. The scatter for both sets of data, however, increases rapidly in the critical region.

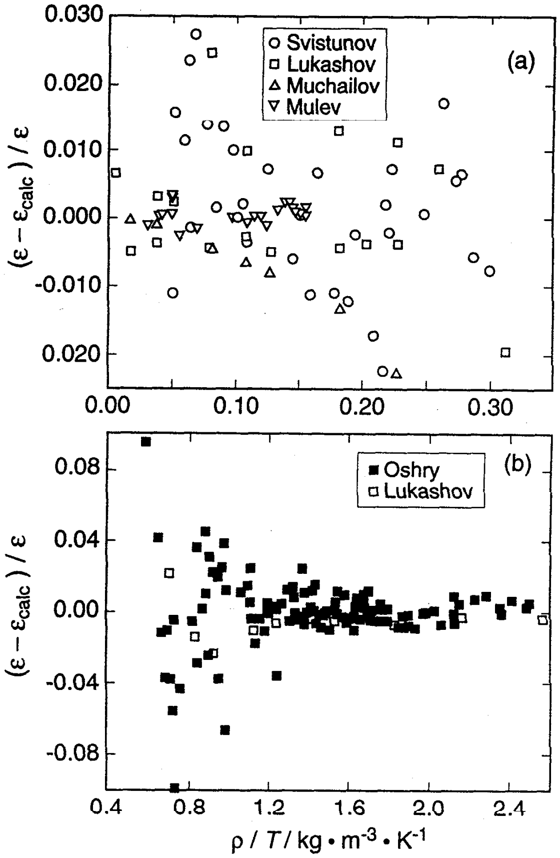

FIG. 7. Comparison of experimental data for the dielectric constant of water along the saturation line. (a) saturated vapor; (b) saturated liquid.

6. Region C:
One-Phase Region Above 373.15 K

Table 6 shows the data sets for the one-phase region between 473 K and 873 K. The densities investigated range from 50 kg·m^{-3} to 1056 kg·m^{-3}, and the pressures go up to 573 MPa. Only low-frequency methods have been employed in this region, in which the capacitance cell must withstand extreme conditions. The file names in Table 6 identified with an asterisk represent the most consistent data.

Fogo *et al.*[54] were the first experimenters concerned with the dielectric constant of supercritical water in connection with the conductivity of sodium chloride in steam. They used a resistive ratio-arms bridge operated at frequencies below 8 kHz, previously set up for resistance measurements. The capacitance cell was made out of platinum-iridium cylindrical electrodes with sapphire insulators. Fogo *et al.*[54] considered the frequency dependence of the capacitance cell filled with steam, although they did not report the conductivity. They also studied the lead capacitance, which they found temperature and frequency dependent. Figure 8 shows eight of the nine isochores reported by Fogo *et al.*[54] in the critical region. Also presented smoothed data for nominal temperatures and densities; the root-mean-square deviation of the smoothed points from the curve that fit the points is about 2%, which is the value for the experimental uncertainty listed in Table 6.

The dielectric constant and specific conductivity of water were measured by Gier and Young[62] at 10 kHz with a platinum-sapphire cell. The conductivities reported are up to about three times the value obtained from other measurements.[16] Gier and Young[62] fit the four isotherms as a function of pressure, finding average residuals between 3% and 10%, depending on the isotherm. As can be seen in Figs. 9a and 9b, the data by Gier and Young[62] deviate systematically from other measurements[41,44] along the same isotherm. In Fig. 9, all the data were fitted with a fourth-order polynomial in the density, while equal weights were used.

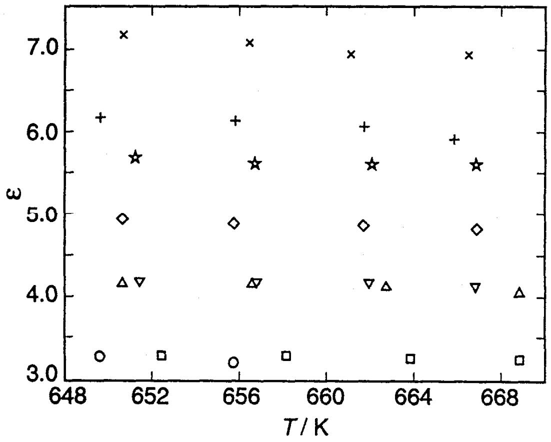

FIG. 8. The dielectric constant of water obtained by Fogo *et al.*[54] in the critical region. ρ in kg·m^{-3}: (○) 213.6; (□) 229.0; (△) 261.3; (▽) 286.5; (◇) 300.8; (☆) 334.3; (+) 344.3; (×) 402.0.

Heger[41] studied the one-phase region from dilute steam to liquid-like densities and temperatures up to 823 K. The cell used by Heger[41] consisted of two coaxial half cylinders made of silver and gold-palladium alloy, with alumina insulators; the electrodes could be rotated in order to study the effect of the lead capacities. The capacitance of the cell filled with water was measured at 100 kHz with a ratio-transformer bridge for two positions of the electrodes, and the lead capacitance could be eliminated by this procedure. The conductance was measured simultaneously with the capacitance and used, together with the inductance of the capacitor plus leads, to correct the measured capacitance. The water in the cell was renewed each time the conductivity rose above 10 mS·m^{-1}. The uncertainty claimed by Heger[41] was about ±0.3%, and about ±2% at the critical point. For the 673 K isotherm, however, the Heger[41] and Deul[44] data differ by up to 6%. In Figure 9, the data of Heger[41] are compared with other data along four isotherms.

Golubev[58] made measurements at densities up to 200 kg·m^{-3} in the one-phase region at temperatures between 693 K and 783 K. A stainless-steel cell with ceramic insulators together with a ratio transformer bridge at 20 kHz were used to measure the capacitance of the cell filled with water. The vacuum capacitance was obtained from the dimensions of the cell and from measurements with other liquids of known ϵ. It is not possible to compare directly the data obtained by Golubev[58] with values reported by others since they were not taken at the same temperatures. Figure 10 shows the residuals obtained when the data reported by Golubev[58] are fitted with a third-degree polynomial in the density.

The papers by Lukashov[47,55] were introduced in Sec. 5. Lukashov[47] measured extensively the dielectric constant in the one-phase region, in addition to measurements along the phase boundary, for steam and for the liquid phase. The conductivity of the water used, 470 μS·m^{-1} at $T = 524$ K and close to the phase boundary, is about 50% higher than the lowest value currently accepted [16] for pure water. This is probably the best conductivity attained in this region for measurement of the dielectric constant of water.

Deul[44] measured the dielectric constant of pure water and the dielectric constant and density of water-benzene mixtures. He used a cell constructed from a nickel-copper-silver alloy

TABLE 6. Region C

Ref.	File Name	T/K	ρ/kg·m^{-3}	Method[a](f/kHz)	Reference	No. of Data	Uncertainty[e]/%
54	C54Fogo*	637–669	214–503	CB(0.4–8)	vacuum	33	2
62	C63Gier	473–623	575–951	CB(10)	unspecified	22	3–10[b]
41	C69Hege*	473–823	79–1056	CB(100)	vacuum	104	0.3–18[c]
55	C75Luka	673–873	80–400	CB(1–20)	vacuum[d]	23	
58	C78Golu*	693–783	32–199	CB(20)	vacuum[d]	57	2
47	C81Luka*	621–873	50–900	CB(15–20)	vacuum[d]	71	0.8
44	C84Deul*	473–673	498–1000	LCR(10–1000)	vacuum	89	0.24–1

[a] CB=capacitance bridge; LCR= impedance meter.
[b] scatter of the data for the different isotherms.
[c] for a detailed error assigment see Ref. 63.
[d] vacuum capacitance calculated from the dimensions of the cell.
[e] as given by the author(s).
*data recommended for use in data correlations.

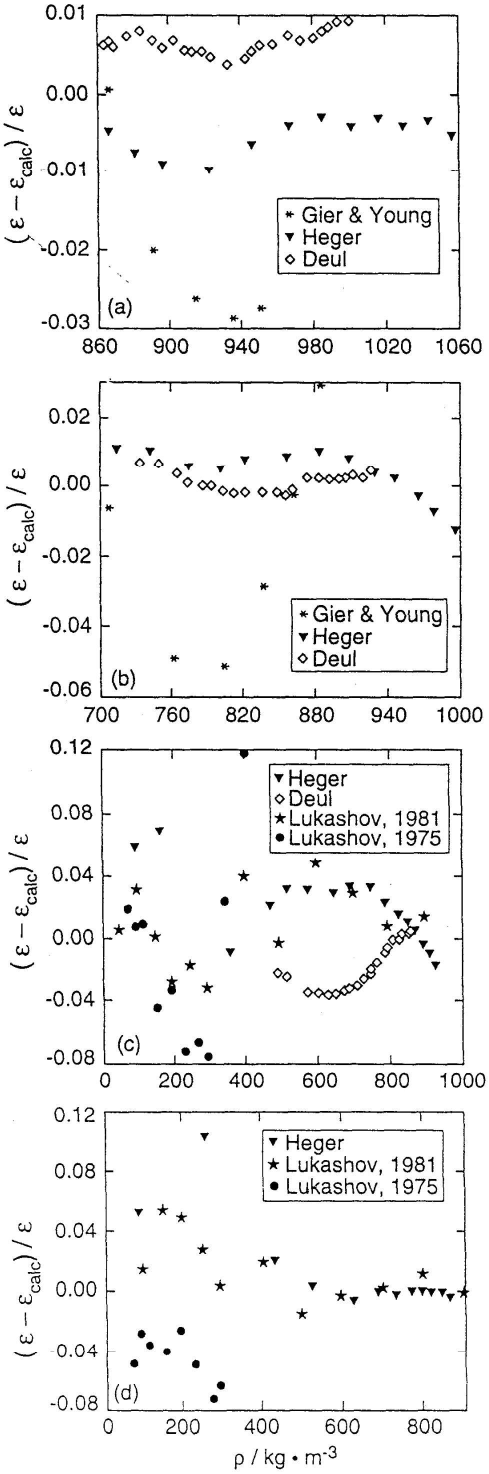

FIG. 9. Comparison of experimental data for the dielectric constant of water for isotherms between 473 K and 773 K, and densities up to 1060 kg·m^{-1}. T in K: (a) 473; (b) 573; (c) 673; (d) 773.

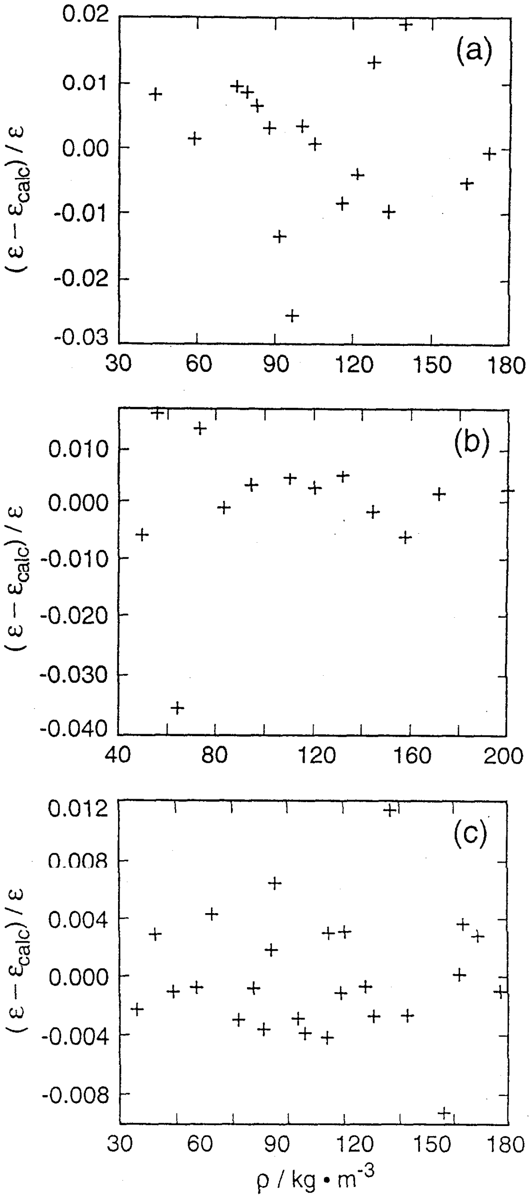

FIG. 10. Experimental data for the dielectric constant of water obtained by Golubev between 693 K and 783 K, and densities up to 200 kg·m^{-1}. T in K: (a) 693; (b) 743; (c) 783.

and an *LCR* meter operating at a frequency of 10 kKz. 100 kHz and 1 MHz. The conductivity of the water in the cell was, at most, 9 $\mu S \cdot m^{-1}$

Figure 9 shows the comparison of the data obtained by Gier and Young,[62] Heger,[41] Lukashov,[47,55] and Deul.[44] The agreement deteriorates with increase of the temperature, especially at low densities. Apart from the data by Gier and Young,[62] the agreement at 473 K and 573 K is better than 2% and 3%, respectively. At 673 K the data by Heger[41] agree with the data of Lukashov[47] within 5% at densities greater than 500 $kg \cdot m^{-3}$, while the data of Deul[44] are 8% lower than those of Heger and Lukashov at 600 $kg \cdot m^{-3}$. The values for $(\partial \epsilon / \partial \rho)_{T=673K}$ calculated from the data of Heger[41] and Deul[44] at 800 $kg \cdot m^{-3}$ differ by 16%. At 773 K the data of Heger[41] and Lukashov[47] agree within 5%, deteriorating at the lower densities; the older data by Lukashov,[55] below 300 $kg \cdot m^{-3}$, appear to be systematically low.

7. Region D: Supercooled Water

An important concern in the experimentation with supercooled water is the avoidance of crystallization. Bulk samples can be supercooled a few degrees below the normal freezing point at 273.15 K. A capacitance cell with an estimated volume of several cubic centimeters was used by Rusche[39] to measure the dielectric contant of water down to temperatures of 268 K. The degree of supercooling can be increased by reducing the size of the sample, as in capillary tubes or small parallel-plate capacitors; this was the method followed by Bertolini *et al.*,[43] who measured in the supercooled liquid at ambient pressure down to 256.9 K. Water emulsions can be easily cooled well below those temperatures where bulk water freezes spontaneously. Hasted and Shahidi,[64] and Hodge and Angell[65] estimated the dielectric constant of water down to 238.16 K using an emulsion in a non-polar medium. The four experiments mentioned above reporting dielectric constant data for supercooled water at ambient pressure are summarized in Table 7. The file names identified with an asterisk represent the most consistent data.

Rusche[39] used a capacitance cell made of coaxial platinum-gold electrodes, similar to the one used by Vidulich *et al.*[19,22]. The frequency dependence of the capacitor filled with a very pure sample was studied between 0.5 kHz and 20 kHz with a transformer bridge. The experimental capacitances were extrapolated to infinite frequency to obtain the dielectric constant of water: the difference between the experimental value of the capacitance at 10 kHz and the extrapolated value at $f = \infty$ was 0.04% for the example shown at room temperature. Some aspects of the data obtained by Rusche[39] above 273.15 K were discussed in Sec. 4.1.2; the data in the supercooled regime were corrected in the same fashion as described in Sec. 4.1.2.

Hasted and Shahidi[64] studied the static dielectric constant of emulsions of water in *n*-hexane, with polyoxyethylene sorbitan triesterate as surfactant agent. The dielectric constant measured for the emulsion ϵ_m was related to the dielectric constants of pure water ϵ_1 and *n*-hexane ϵ_2 through the equation,

$$\frac{\epsilon_m - \epsilon_2}{3\epsilon_2} = \nu \frac{\epsilon_1 - \epsilon_2}{2\epsilon_2 + \epsilon_1} \tag{11}$$

where ν is a parameter associated with the volume fraction of water. The value for ν was obtained from the data of Malmberg and Maryott[20] between 273.15 K and 293.14 K and from the measured values for the dielectric constant of pure hexane, ϵ_2, and of the emulsion, ϵ_m, in the same temperature range. This value of ν which agrees within 1% with the volumetrically-determined value, was then used to calculate the dielectric constant of water ϵ_1 in the supercooled region. Two volume fractions of water were used, 0.5% and 1%. The values for the dielectric constant of supercooled water obtained for the 1% water emulsion are lower than the values obtained with 0.5% water emulsion. The agreement between the two sets of data is better than the uncertainty of 2% estimated by the authors.

Hodge and Angell[65] studied the relaxation time attributed to the interfacial polarization of water droplets emulsified in a solution of *n*-heptane and carbon tetrachloride. The volume fraction of water was 30% and sorbitan triesterate was used as emulsifying agent. The description of the polarization at the interface by the Maxwell-Wagner theory is hampered by the fact that the interface includes this polar molecule in an appreciable concentration. According to this theory, the relaxation time is simply proportional to the product of the real permittivity and dielectric loss (or inverse conductivity). Hodge and Angell[65] developed a data analysis based on the Maxwell-Wagner theory by which they were able to estimate values for the static dielectric constant and conductivity for the supercooled droplets. The dielectric constant data obtained agree within 2% with the extrapolation of the data of Malmberg and Maryott[20] or Vidulich *et al.*.[22] The value of conductivity

TABLE 7. Region D

Ref.	File Name	T/K	Phase	Method[a](f/MHz)	Reference	No. of Data	Uncertainty[c]/%
39	D66Rusc*	268–273	bulk	CB(0.0005–0.05)	vacuum	14	0.035
64	D76Hast	238–268	emulsion	ML(0.001652)	ref. 20	7	2
65	D78Hodg*	238–263	emulsion	MW(0.05–3)	vacuum	6	2
43	D82Bert*	257–272	bulk	RC(27.5)	ref. 20	6	1[b]

[a] CB=capacitance bridge; ML=Maxwell-Lewin dielectric mixture; RC=resonance circuit; MW=Maxwell-Wagner interfacial polarization.

[b] scatter of the points.

[c] as given by the author(s).

*data recommended for use in data correlations.

obtained at 273.15 K, however, was more than three orders of magnitude larger than that of pure water[16] at the same temperature.

Bertolini *et al.*[43] studied the complex permittivity of water in capillary tubes at 9.61 GHz, with a resonance cavity technique. They also measured in a different experiment the static dielectric constant of supercooled water at 27.5 MHz with a 4 mm^3 parallel-plate capacitor in a resonant circuit. The calibration of the method was accomplished by measuring the resonance frequency of the capacitor in vacuum and filled with water, between 273.15 K and 313 K; the constants of the resonant circuit were then obtained using the data of Malmberg and Maryott[20] in the same temperature range. The values obtained for the static dielectric constant of supercooled water in this way were fitted, together with unspecified data from the literature. The values reported were interpolated from this fit, with a residual standard deviation of less than 1%.

Figure 11 shows the residual deviations obtained when all the supercooled data are fitted with a fourth-order polynomial in the temperature. The data of Hasted and Shahidi[64] fall about 2% above the other data. On the other hand, the data of Rusche,[39] Hodge and Angell,[65] and Bertolini, *et al*[43] seem to have a consistent slope. The data reported by Bertolini *et al.*[43] are lower than the other data at the same temperature. The difference is in part explained by the calibration Bertolini *et al.*[43] selected, using the data of Malmberg and Maryott[20] as a reference. Close to T_f, the data of Malmberg and Maryott[20] are 0.2% lower than the average, as can be inferred in Fig. 5.

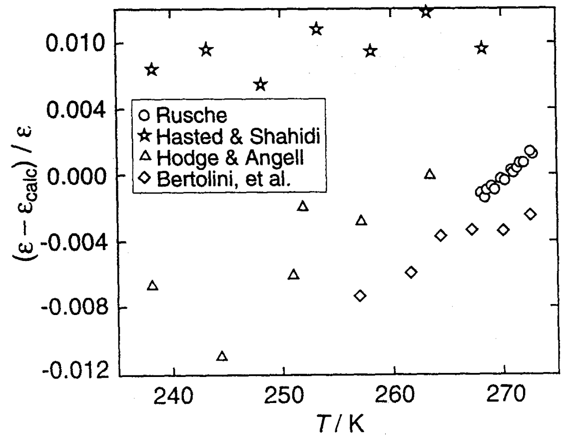

FIG. 11. Comparison of experimental data for the dielectric constant of supercooled water.

8. Conclusions

In this paper, the entire original database for the static dielectric constant of water and steam has, for the first time, been entered into the archival literature, and made available on diskette. In addition, the data have been evaluated, corrected when necessary, and transformed to the ITS–90 temperature scale. In the process, many discrepancies between data sources have been noted, and some of these have been understood by new measurements, the results of which are included in the present work.

The major uncertainties in the dielectric constant of water occur in the supercritical regime. There are few data sources in this region, and discrepancies of up to 10% have been noted, especially in the highly compressible region at densities below 500 kg·m^{-3}, a region of considerable practical importance. In this latter regime, however, the static permittivity is no larger than 10, and electrolytic contamination should not be important. The intrinsic conductivity of the fluid, moreover, is below 60 μS·m^{-1}, no greater than that of liquid water at the boiling point, where the uncertainty of the measured dielectric constant is only 0.3%.

For these reasons, it is not likely that losses due to the conductivity of water play a major role in explaining the 10% discrepancies in the supercritical regime at low and intermediate densities.

It would be interesting to further investigate this region with low- or high-frequency methods, in order to resolve these discrepancies.

We are in the process of preparing a new formulation of the dielectric constant of water and steam on the basis of the corrected data presented here, and making use of a formulation of the equation of state of water based on ITS–90.

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11. Appendix

Originial and Corrected Static Dielectric Constant Data for Water and Steam

Region A: liquid water between 273.15 K and 373.12 K

A30Drak.at $p=p_0$ Ref. 24

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
298.15	78.57	298.135	78.61

A30Wyma.at $p=p_0$ Ref. 26

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
294.25	79.99	294.237	80.03
310.05	74.65	310.031	74.69
311.35	74.06	311.330	74.10
298.15	78.49	298.135	78.53
294.45	79.75	294.437	79.79
293.15	80.29	293.137	80.33
291.55	84.80	–	–

A32Aker.at $p=p_0$ Ref. 29

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
283.15	84.20	283.148	84.25
293.15	80.37	293.138	80.41
298.15	78.54	298.135	78.58
303.15	76.73	303.133	76.77
313.15	73.12	313.130	73.16
323.15	69.85	323.127	69.89
333.15	66.62	333.124	66.66
343.15	63.50	343.124	63.53
353.15	60.60	353.123	60.63
363.15	57.80	363.124	57.83
373.15	55.10	373.124	55.13

A37Albr.at $p=p_0$ Ref. 30

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
291.15	81.13	291.139	81.17
298.15	78.48	298.135	78.52
301.15	77.41	301.134	77.45
323.15	69.95	323.127	69.99

Region A: liquid water between 273.15 K and 373.12 K — Continued

A38Wyma.at $p=p_0$ Ref. 27

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
273.15	88.15	273.150	88.20
283.15	84.15	283.144	84.20
293.15	80.36	293.138	80.40
298.15	78.54	298.135	78.58
303.15	76.76	303.133	76.80
313.15	73.35	313.130	73.39
323.15	70.10	323.127	70.14
333.15	67.00	333.124	67.04
343.15	64.05	343.124	64.09
353.15	61.22	353.123	61.25
363.15	58.51	363.124	58.54
373.15	55.90	373.124	55.93

A39Tyss.at $p=p_0$ Ref. 31

T/K	ϵ(orig.)	T ITS–90/K
293.29	80.27	293.278
293.29	80.21	293.278
293.29	80.24	293.278
293.29	80.24	293.278
293.29	80.32	293.278
293.29	80.23	293.278
293.29	80.30	293.278
298.03	78.60	298.016
298.03	78.47	298.016
298.06	78.51	298.046
298.04	78.49	298.026
298.04	78.60	298.026
298.04	78.50	298.026
298.07	78.55	298.056

A46Albr.at $p=p_0$ Ref. 32

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
278.15	86.10	278.147	86.15
288.15	82.19	288.140	82.23
298.15	78.48	298.135	78.52
308.15	74.94	308.132	74.98
318.15	71.50	318.128	71.54
328.15	68.13	328.126	68.17

Region A: liquid water between 273.15 K and 373.12 K — Continued

A49Lees Ref. 33

T/K	*p*(orig.)/MPa	ϵ(orig.)	*T* ITS–90/K	*p*(corr.)/MPa
296.55	0.1013	78.969	296.536	0.1013
273.15	0.0981	87.915	273.150	0.0981
273.15	19.61	88.718	273.150	19.81
273.15	98.07	91.778	273.150	99.09
273.15	196.13	95.278	273.150	198.17
273.15	294.20	98.518	273.150	297.26
273.15	392.27	101.565	273.150	396.35
273.15	588.40	107.262	273.150	594.53
283.15	0.0981	83.978	283.144	0.0981
283.15	19.61	84.745	283.144	19.81
283.15	98.07	87.650	283.144	99.09
283.15	196.13	90.969	283.144	198.17
283.15	392.27	96.919	283.144	396.35
283.15	490.33	99.661	283.144	490.33
283.15	588.40	102.300	283.144	594.53
283.15	735.50	106.076	283.144	743.16
293.15	0.0981	80.217	293.138	0.0981
293.15	19.61	80.958	293.138	19.81
293.15	98.07	83.740	293.138	99.09
293.15	196.13	86.901	293.138	198.17
293.15	294.20	89.828	293.138	297.26
293.15	588.40	97.671	293.138	594.53
293.15	862.99	104.211	293.138	871.97
303.15	0.0981	76.613	303.133	0.0981
303.15	19.61	77.324	303.133	19.81
303.15	98.07	80.001	303.133	99.09
303.15	196.13	83.039	303.133	198.17
303.15	294.20	85.832	303.133	297.26
303.15	588.40	93.308	303.133	594.53
303.15	980.67	101.925	303.133	990.88
303.15	1029.70	103.046	303.133	1040.42
323.15	0.0981	69.929	323.127	0.0981
323.15	19.61	70.607	323.127	19.81
323.15	98.07	73.136	323.127	99.09
323.15	196.13	75.972	323.127	198.17
323.15	294.20	78.571	323.127	297.26
323.15	588.40	85.417	323.127	594.53
323.15	1176.80	96.992	323.127	1189.05

A53Harr1 Ref. 34

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
298.75	0.1013	78.34	298.735
298.75	7.822	78.66	298.735
298.75	12.889	78.78	298.735

Region A: liquid water between 273.15 K and 373.12 K — Continued

A53Harr2 Ref. 35

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K	ϵ(corr.)
287.65	0.1013	82.39	287.640	82.43
287.65	7.447	82.73	287.640	82.78
287.65	12.200	82.89	287.640	82.94
287.65	14.611	83.00	287.640	83.05
298.75	0.1013	78.31	298.735	78.35
298.75	7.822	78.63	298.735	78.67
298.75	12.889	78.75	298.735	78.79
309.05	0.1013	74.68	309.031	74.72
309.05	4.479	74.79	309.031	74.83
309.05	8.511	74.85	309.031	74.89
309.05	10.852	74.93	309.031	74.97
320.65	0.1013	70.92	320.628	70.96
320.65	5.137	70.95	320.628	70.99
320.65	10.102	71.01	320.628	71.05
320.65	14.885	71.05	320.628	71.09
320.65	19.059	71.08	320.628	71.12
333.85	0.1013	66.99	333.824	67.03
333.85	9.616	67.05	333.825	67.09
333.85	13.750	67.05	333.825	67.09
333.85	17.701	67.05	333.825	67.09
347.65	3.759	63.37	347.624	63.40
347.65	7.346	63.33	347.624	63.36
347.65	10.892	63.60	347.624	63.63
347.65	14.094	63.60	347.624	63.63

A55Miln Ref. 36

T/K	*p*/MPa	f/MHz	*T* ITS–90/K	ϵ(corr.)
273.160	0.1013	51.1765	273.160	87.922
273.155	10.141	51.0633	273.155	88.312
273.155	20.217	50.9531	273.155	88.694
273.169	30.297	50.8455	273.169	89.070
273.162	40.350	50.7326	273.162	89.467
273.162	50.414	50.6154	273.162	89.881
273.154	60.481	50.5049	273.154	90.275
273.162	70.598	50.4050	273.162	90.633
273.162	80.650	50.2978	273.162	91.020
273.161	90.788	50.1750	273.161	91.466
273.162	100.921	50.0761	273.162	91.820
278.150	0.1013	51.7684	278.147	85.923
278.150	10.141	51.6531	278.147	86.307
278.147	20.217	51.5436	278.144	86.674
278.157	30.297	51.4236	278.154	87.079
278.158	40.350	51.3134	278.155	87.453
278.158	50.414	51.2034	278.155	87.829
278.159	60.481	51.0939	278.156	88.206
278.145	70.598	50.9844	278.142	88.585
278.150	80.650	50.8734	278.147	88.972
278.151	90.788	50.7829	278.148	89.290
278.151	100.921	50.6830	278.148	89.642
283.150	0.1013	52.3786	283.144	83.933
283.146	10.141	52.2540	283.140	84.334
283.146	20.217	52.1334	283.140	84.725
283.150	30.297	52.0208	283.142	85.092
283.146	40.350	51.8985	283.140	85.493
283.148	50.414	51.7890	283.142	85.855
283.148	60.481	51.6807	283.142	86.215
283.146	70.598	51.5657	283.140	86.600
283.150	80.650	51.4575	283.144	86.964
283.148	90.788	51.3530	283.142	87.319
283.148	100.921	51.2523	283.142	87.662

Region A: liquid water between 273.15 K and 373.12 K — Continued

A55Miln Ref. 36 — Continued

T/K	*p*/MPa	f/MHz	*T* ITS–90/K	ϵ(corr.)
288.141	0.1013	52.9793	288.131	82.041
288.148	10.141	52.8497	288.138	82.444
288.141	20.217	52.7284	288.131	82.824
288.142	30.297	52.6121	288.132	83.190
288.141	40.350	52.4991	288.131	83.549
288.141	50.414	52.3828	288.131	83.920
288.142	60.481	52.2749	288.132	84.267
288.141	70.598	52.1552	288.131	84.654
288.141	80.650	52.0539	288.131	84.984
288.141	90.788	51.9427	288.131	85.348
288.141	100.921	51.8431	288.131	85.676
293.155	0.1013	53.5894	293.143	80.185
293.147	10.141	53.4644	293.135	80.560
293.149	20.217	53.3448	293.137	80.921
293.147	30.297	53.2271	293.135	81.280
293.156	40.350	53.1098	293.144	81.639
293.156	50.414	52.9851	293.144	82.023
293.151	60.481	52.8752	293.139	82.365
293.150	70.598	52.7615	293.138	82.720
293.150	80.650	52.6512	293.138	83.067
293.149	90.788	52.5463	293.137	83.399
293.149	100.921	52.4386	293.137	83.742
298.147	0.1013	54.2117	298.133	78.355
298.145	10.141	54.0853	298.131	78.721
298.145	20.217	53.9573	298.131	79.095
298.142	30.297	53.8309	298.128	79.467
298.157	40.350	53.7156	298.143	79.808
298.157	50.414	53.5932	298.143	80.173
298.157	60.481	53.4776	298.143	80.520
298.157	70.598	53.3679	298.143	80.851
298.157	80.650	53.2540	298.143	81.197
298.158	90.788	53.1466	298.144	81.526
298.158	100.921	53.0366	298.144	81.864

A55Scai Ref. 37

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
293.15	0.1013	81.0	293.138
293.15	65.7	83.4	293.138
293.15	131.4	85.5	293.138
293.15	197.1	88.7	293.138
293.15	262.8	90.4	293.138
293.15	358.9	93.4	293.138
293.15	424.6	95.4	293.138
293.15	490.3	97.0	293.138
293.15	556.0	99.0	293.138
293.15	588.4	100.0	293.138

Region A: liquid water between 273.15 K and 373.12 K — Continued

A56Gran.at $p=p_0$ Ref. 23

T/K	ϵ(orig.)	λ/m	*T* ITS–90/K	ϵ(corr.)
273.15	88.1	0.520	273.150	88.1
273.15	85.3	0.172	273.150	–
283.15	84.0	0.520	283.144	84.0
283.15	82.4	0.172	283.144	–
293.15	80.3	0.520	293.138	80.3
293.15	79.2	0.172	293.138	–
303.15	76.6	0.520	303.133	76.6
303.15	76.1	0.172	303.133	–
313.15	73.3	0.520	313.130	73.3
313.15	72.9	0.172	313.130	–
323.15	69.9	0.520	323.127	69.9
323.15	69.7	0.172	323.127	–
333.15	66.8	0.520	333.124	66.8
333.15	66.7	0.172	333.124	–
343.15	63.7	0.172	343.124	–

A56Malm.at $p=p_0$ Ref. 20

T/K	ϵ(orig.)	*T* ITS–90/K
273.25	87.696	273.250
278.15	85.764	278.147
283.15	83.834	283.142
288.15	81.950	288.136
293.15	80.100	293.138
298.15	78.301	298.135
303.15	76.540	303.133
308.15	74.832	308.132
313.15	73.149	313.130
318.15	71.508	318.128
323.15	69.917	323.127
328.15	68.345	328.126
333.15	66.820	333.124
338.15	65.317	338.124
343.15	63.859	343.124
348.15	62.418	348.123
353.15	61.019	353.123
358.15	59.658	358.123
363.15	58.314	363.124
368.15	57.008	368.124
372.15	55.985	372.125

A58Coga Ref. 38

T/K	*p*/MPa	*f*/MHz	*T* ITS–90/K	ϵ(corr.)
298.140	0.10	54.265	298.125	78.228
298.144	10.14	54.133	298.129	78.610
298.143	20.12	54.008	298.128	78.974
298.144	30.25	53.887	298.129	79.329
298.141	40.35	53.763	298.126	79.695
298.141	50.25	53.650	298.126	80.031
298.141	60.48	53.529	298.126	80.393
298.141	70.60	53.415	298.126	80.737
298.141	80.65	53.304	298.126	81.073
298.139	90.79	53.191	298.124	81.418
298.142	100.97	53.082	298.127	81.753
303.144	0.10	54.838	303.127	76.576
303.143	10.14	54.706	303.126	76.946
303.141	20.22	54.581	303.124	77.298
303.144	30.30	54.458	303.127	77.648

Region A: liquid water between 273.15 K and 373.12 K — Continued

A58Coga Ref. 38 — Continued

T/K	p/MPa	f/MHz	T ITS–90/K	ϵ(corr.)
303.144	40.35	54.336	303.127	77.997
303.145	50.41	54.212	303.128	78.354
303.141	60.48	54.093	303.124	78.699
303.140	70.60	53.974	303.123	79.046
303.144	80.65	53.862	303.127	79.375
303.140	90.79	53.742	303.123	79.730
303.140	100.92	53.630	303.123	80.063
308.141	0.10	55.517	308.122	74.741
308.141	10.14	55.389	308.122	75.087
308.141	20.21	55.255	308.122	75.451
308.141	30.30	55.123	308.122	75.813
308.141	40.35	54.998	308.122	76.158
308.137	50.41	54.878	308.118	76.491
308.139	60.48	54.762	308.120	76.815
308.140	70.60	54.641	308.121	77.156
308.141	80.65	54.523	308.122	77.490
308.142	90.79	54.414	308.123	77.801
308.136	100.92	54.298	308.117	78.133
313.136	0.10	56.100	313.116	73.153
313.134	10.14	55.966	313.114	73.503
313.133	20.22	55.836	313.113	73.846
313.139	30.30	55.704	313.119	74.196
313.140	40.35	55.573	313.120	74.546
313.139	50.41	55.451	313.119	74.875
313.139	60.48	55.326	313.119	75.213
313.138	70.60	55.206	313.118	75.540
313.138	80.65	55.091	313.118	75.856
313.140	90.79	54.971	313.120	76.187
313.138	100.92	54.858	313.118	76.501
318.140	0.10	56.743	318.118	71.505
318.136	10.14	56.606	318.114	71.851
318.137	20.22	56.468	318.115	72.203
318.137	30.30	56.335	318.115	72.544
318.136	40.35	56.204	318.114	72.882
318.137	50.41	56.077	318.115	73.213
318.136	60.48	55.950	318.114	73.545
318.136	70.60	55.829	318.114	73.864
318.137	80.65	55.709	318.115	74.183
318.136	90.79	55.590	318.114	74.501
318.138	100.92	55.471	318.116	74.821
323.139	0.10	57.399	323.116	69.897
323.141	10.14	57.258	323.118	70.225
323.140	20.22	57.117	323.117	70.534
323.139	30.30	56.982	323.116	70.923
323.140	40.35	56.847	323.117	71.206
323.141	50.41	56.718	323.118	71.585
323.142	60.48	56.583	323.119	71.910
323.141	70.60	56.458	323.118	72.228
323.138	80.65	56.334	323.115	72.546
323.138	90.79	56.215	323.115	72.854
323.138	100.92	56.095	323.115	73.166
328.119	0.10	58.048	328.095	68.327
328.117	10.14	57.903	328.093	68.669
328.120	20.22	57.762	328.096	69.005
328.118	30.30	57.619	328.094	69.348
328.115	40.35	57.484	328.091	69.674
328.119	50.41	57.351	328.095	69.997
328.121	60.48	57.218	328.097	70.323
328.122	70.60	57.090	328.098	70.638
328.125	80.65	56.970	328.101	70.936
328.124	90.79	56.847	328.100	71.243
328.126	100.92	56.731	328.102	71.535
333.137	0.10	58.711	333.111	66.793

Region A: liquid water between 273.15 K and 373.12 K — Continued

A58Coga Ref. 38 — Continued

T/K	*p*/MPa	*f*/MHz	*T* ITS–90/K	ϵ(corr.)
333.138	10.14	58.568	333.112	67.119
333.137	20.22	58.420	333.111	67.460
333.138	30.30	58.277	333.112	67.791
333.136	40.35	58.138	333.110	68.115
333.140	50.41	58.007	333.114	68.423
333.139	60.48	57.869	333.113	68.750
333.131	70.60	57.732	333.105	69.077
333.137	80.65	57.606	333.111	69.379
333.138	90.79	57.478	333.112	69.688
333.134	100.92	57.360	333.108	69.975
338.141	0.10	59.415	338.115	65.220
338.141	10.14	59.261	338.115	65.559
338.141	20.22	59.112	338.115	65.890
338.141	30.30	58.965	338.115	66.219
338.139	40.35	58.823	338.113	66.539
338.138	50.41	58.681	338.112	66.861
338.137	60.48	58.544	338.111	67.174
338.136	70.60	58.411	338.110	67.480
338.144	80.65	58.286	338.118	67.770
338.138	90.79	58.152	338.112	68.083
338.138	100.92	58.028	338.112	68.374
343.144	0.10	60.095	343.118	63.753
343.141	10.14	59.932	343.115	64.100
343.141	20.22	59.778	343.115	64.430
343.140	30.30	59.625	343.114	64.761
343.148	40.35	59.481	343.122	65.075
343.142	50.31	59.340	343.116	65.385
343.145	60.48	59.199	343.119	65.696
343.142	70.68	59.060	343.116	66.006
343.142	80.65	58.928	343.116	66.302
343.142	90.80	58.794	343.116	66.604
343.142	100.92	58.664	343.116	66.900

A62Vidu.at $p=p_0$ Refs. 19 and 22

T/K	ϵ(orig.)	*T* ITS–90/K
273.15	87.910	273.150
278.15	85.890	278.147
283.15	83.960	283.144
288.15	82.110	288.140
293.15	80.200	293.138
298.15	78.390	298.135
313.15	73.190	313.130

A66Rusc.at $p=p_0$ Ref. 39

T/K	ϵ(orig.)	*T* ITS–90/K	ϵ(corr.)
292.15	80.726	292.138	80.666
284.16	83.738	284.152	83.678
283.23	84.098	283.224	84.038
282.39	84.435	282.384	84.375
281.53	84.754	281.525	84.694
280.66	85.095	280.655	85.035
279.81	85.436	279.805	85.376
278.95	85.768	278.946	85.708
278.07	86.121	278.067	86.061
277.19	86.466	277.187	86.406
277.09	86.496	277.087	86.436
276.30	86.816	276.297	86.756

Region A: liquid water between 273.15 K and 373.12 K — Continued

A66Rusc.at $p=p_0$ Ref. 39 — Continued

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
275.42	87.167	275.418	87.107
274.53	87.533	274.529	87.473
273.66	87.880	273.660	87.820
298.23	78.522	298.215	78.462
297.46	78.801	297.446	78.741
296.56	79.130	296.546	79.070
295.62	79.462	295.606	79.402
294.67	79.817	294.657	79.757
293.72	80.166	293.708	80.106
292.74	80.515	292.728	80.455
291.77	80.877	291.758	80.817
290.76	81.229	290.749	81.169
289.85	81.585	289.840	81.525
288.90	81.951	288.890	81.891
287.98	82.288	287.970	82.228
287.91	82.320	287.900	82.260
286.93	82.688	286.921	82.628
285.93	83.061	285.922	83.001
284.96	83.439	284.952	83.379
283.94	83.825	283.933	83.765
282.97	84.212	282.964	84.152
281.95	84.601	281.944	84.541
280.93	84.996	280.924	84.936
279.97	85.391	279.965	85.331
278.92	85.788	278.916	85.728
278.63	85.928	278.627	85.868
277.74	86.276	277.737	86.216
276.87	86.615	276.867	86.555
275.97	86.972	275.968	86.912
275.10	87.326	275.099	87.266
274.23	87.677	274.229	87.617
273.35	88.026	273.350	87.966
275.00	87.355	273.999	87.295

A69Scha Ref. 40

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
293.15	0.0981	80.360	293.138
293.15	12.75	81.110	293.138
293.15	25.69	81.600	293.138
293.15	37.95	82.020	293.138
293.15	50.50	82.430	293.138
293.15	61.98	82.450	293.138
293.15	71.78	83.190	293.138
293.15	81.59	83.500	293.138
293.15	91.40	83.990	293.138
293.15	101.01	84.230	293.138
293.15	110.82	84.680	293.138
293.15	119.64	84.720	293.138
293.15	125.53	85.010	293.138
303.15	0.0981	76.650	303.133
303.15	12.75	77.150	303.133
303.15	25.69	77.680	303.133
303.15	37.95	78.000	303.133
303.15	50.50	78.330	303.133
303.15	61.98	78.850	303.133
303.15	71.78	79.350	303.133
303.15	81.59	79.800	303.133
303.15	91.40	80.090	303.133
303.15	101.01	80.510	303.133
303.15	110.82	80.900	303.133

Region A: liquid water between 273.15 K and 373.12 K — Continued

A69Scha Ref. 40 — Continued

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
303.15	119.64	81.130	303.133
303.15	125.53	81.340	303.133
318.15	0.0981	71.200	318.128
318.15	12.75	71.500	318.128
318.15	25.69	71.800	318.128
318.15	37.95	72.210	318.128
318.15	50.50	72.580	318.128
318.15	61.98	72.830	318.128
318.15	71.78	73.100	318.128
318.15	81.59	73.280	318.128
318.15	91.40	73.800	318.128
318.15	101.01	73.980	318.128
318.15	110.82	74.210	318.128
318.15	119.64	74.480	318.128
318.15	125.53	74.750	318.128

A69Hege Ref. 41

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
373.15	0.1	55.300	373.124
373.15	25	56.150	373.124
373.15	50	56.950	373.124
373.15	100	58.400	373.124
373.15	150	59.600	373.124
373.15	200	60.800	373.124
373.15	250	61.900	373.124
373.15	300	62.900	373.124
373.15	350	63.800	373.124
373.15	400	64.700	373.124
373.15	450	65.500	373.124
373.15	500	66.300	373.124

A69Dunn Ref. 21

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
278.15	0.1	85.752	278.147
288.15	0.1	81.972	288.140
293.15	0.1	80.100	293.138
303.15	0.1	76.541	303.133
308.15	0.1	74.818	308.131
313.15	0.1	73.150	313.130
323.15	0.1	69.893	323.127
328.15	0.1	68.336	328.126
333.15	0.1	66.802	333.124
283.15	0.1	83.828	283.144
283.15	16.3	84.421	283.144
283.15	33.9	85.081	283.144
283.15	51.7	85.757	283.144
283.15	68.9	86.374	283.144
283.15	86.2	86.998	283.144
283.15	103.4	87.603	283.144
283.15	120.7	88.237	283.144
283.15	137.9	88.816	283.144
283.15	155.1	89.381	283.144
283.15	172.4	89.948	283.144
283.15	189.6	90.528	283.144
283.15	206.8	91.100	283.144
298.15	0.1	78.304	298.135
298.15	16.3	78.852	298.135

Region A: liquid water between 273.15 K and 373.12 K — Continued

A69Dunn Ref. 21 — Continued

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
298.15	33.9	79.478	298.135
298.15	51.7	80.102	298.135
298.15	68.9	80.676	298.135
298.15	86.2	81.303	298.135
298.15	103.4	81.831	298.135
298.15	120.7	82.401	298.135
298.15	137.9	82.999	298.135
298.15	155.1	83.498	298.135
298.15	172.4	84.023	298.135
298.15	189.6	84.546	298.135
298.15	206.8	85.095	298.135
318.15	0.1	71.503	318.128
318.15	16.3	72.051	318.128
318.15	33.9	72.627	318.128
318.15	51.7	73.251	318.128
318.15	68.9	73.825	318.128
318.15	86.2	74.352	318.128
318.15	103.4	74.899	318.128
318.15	120.7	75.452	318.128
318.15	137.9	75.951	318.128
318.15	155.1	76.415	318.128
318.15	172.4	76.924	318.128
318.15	189.6	77.425	318.128
318.15	206.8	77.900	318.128
338.15	0.1	65.303	338.124
338.15	16.3	65.879	338.124
338.15	33.9	66.451	338.124
338.15	51.7	67.031	338.124
338.15	68.9	67.549	338.124
338.15	86.2	68.018	338.124
338.15	103.4	68.546	338.124
338.15	120.7	69.039	338.124
338.15	137.9	69.502	338.124
338.15	155.1	69.905	338.124
338.15	172.4	70.385	338.124
338.15	189.6	70.848	338.124
338.15	206.8	71.274	338.124

A73Srin Ref. 42

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
283.15	0.1	83.947	283.148
283.15	50.0	85.790	283.148
283.15	100.0	87.587	283.148
283.15	150.0	89.242	283.148
283.15	200.0	90.836	283.148
283.15	250.0	92.284	283.148
283.15	300.0	93.756	283.148
298.15	0.1	78.445	298.144
298.15	50.0	80.239	298.144
298.15	100.0	81.935	298.144
298.15	150.0	83.532	298.144
298.15	200.0	85.053	298.144
298.15	250.0	86.528	298.144
298.15	300.0	88.054	298.144
313.15	0.1	73.157	313.140
313.15	50.0	74.881	313.140
313.15	100.0	76.523	313.140
313.15	150.0	78.014	313.140
313.15	200.0	79.464	313.140
313.15	250.0	80.793	313.140
313.15	300.0	82.089	313.140

Region A: liquid water between 273.15 K and 373.12 K — Continued

A73Srin Ref. 42 — Continued

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K

A81Kaat.at $p=p_0$ Ref. 7

T/K	ϵ(orig.)	*T* ITS–90/K
298.15	78.32	298.144

A82Bert.at $p=p_0$ Ref. 43

T/K	ϵ(orig.)	*T* ITS–90/K
305.50	75.7	305.492
290.75	80.9	290.746
287.30	82.2	287.297
283.40	83.7	283.398
280.00	84.9	279.998
276.65	86.3	276.649
274.90	87.0	274.900

A84Deul Ref. 44

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
298.15	0.1	78.36	298.144
298.15	5.0	78.53	298.144
298.15	10.0	78.72	298.144
298.15	20.0	79.10	298.144
298.15	30.0	79.47	298.144
298.15	40.0	79.83	298.144
298.15	50.0	80.20	298.144
298.15	60.0	80.57	298.144
298.15	70.0	80.91	298.144
298.15	80.0	81.25	298.144
298.15	90.0	81.59	298.144
298.15	100.0	81.92	298.144
298.15	120.0	82.56	298.144
298.15	140.0	83.19	298.144
298.15	150.0	83.50	298.144
298.15	160.0	83.80	298.144
298.15	180.0	84.40	298.144
298.15	200.0	84.95	298.144
298.15	220.0	85.50	298.144
298.15	240.0	86.05	298.144
298.15	250.0	86.28	298.144
298.15	260.0	86.52	298.144
298.15	280.0	87.00	298.144
298.15	300.0	87.51	298.144
373.15	0.1	55.31	373.124
373.15	5.0	55.50	373.124
373.15	10.0	55.71	373.124
373.15	20.0	56.10	373.124
373.15	30.0	56.47	373.124
373.15	40.0	56.82	373.124
373.15	50.0	57.16	373.124
373.15	60.0	57.48	373.124
373.15	70.0	57.80	373.124
373.15	80.0	58.10	373.124
373.15	90.0	58.40	373.124
373.15	100.0	58.68	373.124
373.15	120.0	59.25	373.124
373.15	140.0	59.80	373.124

Region A: liquid water between 273.15 K and 373.12 K — Continued

A84Deul Ref. 44 — Continued

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
373.15	150.0	60.02	373.124
373.15	160.0	60.32	373.124
373.15	180.0	60.80	373.124
373.15	200.0	61.29	373.124
373.15	220.0	61.76	373.124
373.15	240.0	62.20	373.124
373.15	250.0	62.45	373.124
373.15	260.0	62.64	373.124
373.15	280.0	63.08	373.124
373.15	300.0	63.49	373.124

A94Fern.at $p = p_0$ Ref. 45

1. Results obtained with the RT bridge.

T ITS-90/K	ϵ(orig.)	uncertainty
273.174	87.87_7	0.01_5
283.142	83.99_8	0.01_0
293.143	80.226	0.009
298.138	78.388	0.008
298.139	78.401	0.008
298.154	78.406	0.008
303.132	76.637	0.007
313.125	73.216	0.009
313.131	73.195	0.009
323.129	69.94_6	0.01_2
323.139	69.95_2	0.01_2
333.120	66.79_0	0.01_5
343.127	63.86_1	0.02_0
343.134	63.79_7	0.02_0
343.147	63.81_7	0.02_0
353.121	60.96_8	0.03_2
353.128	61.03_9	0.03_2
353.130	61.07_0	0.03_2
353.154	60.95_2	0.03_2
363.127	58.31_7	0.05_2
363.137	58.28_6	0.05_2
373.111	55.71_8	0.08_0
373.113	55.80_8	0.08_0
373.147	55.72_0	0.08_0

2. Results obtained with the LCR meter.

T ITS-90/K	ϵ(orig.)	uncertainty
273.174	87.88_3	0.03_3
283.142	84.01_4	0.01_5
293.143	80.23_9	0.01_1
298.139	78.40_1	0.01_0
298.154	78.41_4	0.01_0
303.132	76.631	0.009
313.125	73.235	0.009
323.129	69.94_6	0.01_1
323.139	69.93_4	0.01_1
343.127	63.82_7	0.01_4
343.134	63.79_0	0.01_4
343.147	63.80_6	0.01_4
353.128	60.94_6	0.01_8

Region A: liquid water between 273.15 K and 373.12 K — Continued

A94Fern.at $p = p_0$ Ref. 45 — Continued

2. Results obtained with the LCR meter.

T ITS-90/K	ϵ(orig.)	uncertainty
353.130	60.91_9	0.01_8
353.154	60.87_8	0.01_8
363.137	58.13_7	0.02_9
373.113	55.50_3	0.04_9
373.147	55.51_5	0.04_9

Region B: saturation curve

BOshr.sl Ref. 28

T/K	ϵ(orig.)	*T* ITS–90/K	ϵ(corr.)
371.6	55.91	371.575	55.94
373.5	55.35	373.474	55.38
381.5	53.67	381.472	53.70
382.4	53.33	382.372	53.36
390.4	51.57	390.381	51.60
397.5	49.49	397.479	49.51
398.0	49.53	397.979	49.55
407.2	47.80	407.177	47.82
414.3	46.16	414.286	46.19
425.2	43.78	425.185	43.81
428.5	43.30	428.484	43.33
428.7	42.63	428.684	42.66
428.8	42.80	428.784	42.83
438.9	40.64	438.893	40.66
442.2	40.32	442.193	40.34
448.5	39.11	448.492	39.13
449.9	38.84	449.892	38.86
456.4	37.35	456.401	37.37
461.3	36.56	461.301	36.58
462.4	36.56	462.401	36.58
465.3	35.85	465.301	35.87
466.4	35.85	466.401	35.87
471.2	34.85	471.200	34.87
478.4	33.97	478.400	33.99
478.5	33.75	478.510	33.77
482.7	33.24	482.710	33.26
483.4	32.92	483.410	32.94
485.1	32.94	485.110	32.96
487.9	32.18	487.910	32.20
490.8	31.73	490.810	31.74
491.8	31.72	491.810	31.73
493.6	31.81	493.610	31.82
494.3	31.24	494.310	31.25
496.0	31.38	496.010	31.39
496.5	31.05	496.510	31.06
498.0	30.94	498.010	30.95
500.7	30.18	500.710	30.19
502.8	30.18	502.810	30.19
504.8	29.76	504.810	29.77
504.9	29.60	504.920	29.61
507.2	28.99	507.220	29.00
508.6	28.97	508.620	28.98
509.6	28.84	509.620	28.85
512.3	28.35	512.320	28.36
513.9	28.52	513.920	28.53
515.2	27.97	515.220	27.98
519.0	27.46	519.020	27.49

Region B: saturation curve — Continued

BOshr.sl Ref. 28 — Continued

T/K	ε(orig.)	*T* ITS–90/K	ε(corr.)
519.9	27.67	519.920	27.69
520.8	27.25	520.820	27.27
521.1	27.32	521.120	27.34
524.2	26.57	524.220	26.59
527.2	26.00	527.220	26.02
528.0	26.15	528.020	26.17
530.6	25.71	530.620	25.73
533.5	25.30	533.520	25.32
535.3	24.85	535.320	24.87
538.7	24.42	538.730	24.44
540.3	24.70	540.330	24.72
541.8	24.11	541.830	24.13
542.0	24.16	542.030	24.18
542.2	24.38	542.230	24.40
545.1	23.67	545.130	23.69
545.3	23.52	545.330	23.54
548.2	23.05	548.230	23.07
549.1	23.35	549.130	23.37
549.4	23.01	549.430	23.03
551.2	23.38	551.230	23.40
552.3	22.56	552.330	22.57
555.9	22.12	555.930	22.13
557.8	22.18	557.830	22.19
558.8	21.92	558.830	21.93
561.4	21.27	561.430	21.28
564.2	21.26	564.230	21.27
569.9	20.29	569.930	20.30
572.2	19.19	572.230	19.20
575.7	19.43	575.730	19.44
577.8	19.19	577.830	19.20
580.4	18.74	580.430	18.75
581.6	18.68	581.630	18.69
581.8	18.62	581.830	18.63
582.2	18.52	582.230	18.53
584.8	17.97	584.830	17.98
588.9	17.53	588.930	17.54
591.3	16.99	591.330	17.00
592.5	17.05	592.540	17.06
595.3	16.68	595.340	16.69
595.4	16.83	595.440	16.84
596.7	16.97	596.740	16.98
597.6	16.69	597.640	16.70
602.5	15.95	602.540	15.96
613.8	14.38	613.840	14.39
614.5	13.24	614.540	13.24
615.1	14.59	615.140	14.60
617.8	14.00	617.839	14.01
619.5	12.92	619.539	12.92
620.3	13.56	620.339	13.57
623.1	13.19	623.139	13.19
625.0	13.02	625.039	13.02
625.9	12.18	625.939	12.18
627.5	12.82	627.539	12.82
627.5	12.38	627.539	12.38
629.2	12.01	629.238	12.01
632.1	11.22	632.138	11.22
632.3	11.94	632.338	11.94
634.7	11.06	634.738	11.06
639.7	9.81	639.737	9.81
641.8	8.91	641.837	8.92
641.9	9.74	641.937	9.75
642.3	9.34	642.337	9.35
642.3	9.18	642.337	9.19

Region B: saturation curve — Continued

BOshr.sl Ref. 28 — Continued

T/K	ε(orig.)	*T* ITS–90/K	ε(corr.)
643.2	9.67	643.237	9.68
643.7	9.27	643.737	9.28
643.8	9.01	643.837	9.02
645.0	8.91	645.037	8.92
645.5	9.24	645.537	9.25
646.7	9.20	646.737	9.21
647.5	8.93	–	–
648.3	9.00	–	–
648.8	8.91	–	–
650.2	9.23	–	–
650.7	9.00	–	–
650.8	8.85	–	–
654.2	8.66	–	–

B75Svis.sv Ref. 51

T/K	ε(orig.)	*T* ITS–90/K
542.0	1.20	542.110
544.0	1.24	544.110
553.0	1.27	553.110
556.3	1.30	556.410
559.0	1.28	559.110
561.5	1.33	561.610
570.5	1.36	570.610
576.5	1.38	576.610
580.0	1.42	580.110
586.0	1.46	586.110
589.0	1.47	589.110
591.0	1.49	591.110
593.0	1.50	593.110
602.0	1.61	602.110
610.5	1.70	610.610
613.0	1.75	613.110
616.0	1.78	616.109
618.0	1.85	618.109
622.0	1.90	622.109
625.0	1.97	625.109
626.5	2.03	626.609
629.5	2.09	629.608
631.0	2.13	631.108
631.5	2.20	631.608
632.0	2.21	632.108
632.5	2.25	632.608
636.5	2.42	636.608
638.5	2.58	638.608
639.5	2.62	639.607
640.0	2.66	640.107
641.0	2.71	641.107
642.0	2.80	642.107

B81Luka.sl Ref. 47

T/K	ε(orig.)	*T* ITS–90/K
373	55.55	373.124
423	43.89	423.115
473	34.59	473.110
523	26.75	523.110
543	23.86	543.110
573	19.66	573.110

Region B: saturation curve — Continued

B81Luka.sl Ref. 47 — Continued

T/K	ϵ(orig.)	T ITS–90/K
593	16.88	593.110
623	12.61	623.109
633	11.22	633.108
643	9.74	643.107

B81Luka.sv Ref. 47

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
423	1.03	423.115	1.03
473	1.06	473.110	1.06
523	1.16	523.110	1.16
543	1.22	543.110	1.22
573	1.39	573.110	1.39
593	1.52	593.110	1.52
623	1.97	623.109	1.97
633	2.28	633.108	2.28
643	2.88	643.107	2.88
647	5.10	–	–
523.15	1.152	523.110	1.152
573.15	1.350	573.110	1.350
593.15	1.501	593.110	1.501
603.15	1.602	603.110	1.602
623.15	1.936	623.109	1.936
628.15	2.071	628.109	2.071
633.15	2.246	633.108	2.246
638.15	2.523	638.108	2.523
643.15	3.022	643.107	3.022

B88Much.sv Ref. 52

T/K	ϵ(orig.)	T ITS–90/K
473.15	1.065	473.110
523.15	1.155	523.110
573.15	1.350	573.110
593.15	1.495	593.110
603.15	1.597	603.110
623.15	1.919	623.109
633.15	2.204	633.108

B94Mule.sv Ref. 53

T/K	ϵ(orig.)	T ITS–90/K
510.31	1.125	510.270
525.13	1.162	525.090
530.14	1.176	530.100
541.10	1.211	541.060
541.34	1.215	541.300
541.77	1.216	541.730
548.82	1.235	548.780
563.64	1.302	563.600
574.39	1.358	574.350
586.71	1.450	586.670
593.32	1.506	593.280
596.69	1.540	596.650
599.18	1.566	599.140
601.98	1.595	601.940
605.77	1.645	605.730

Region B: saturation curve — Continued

B94Mule.sv Ref. 53 — Continued

T/K	ϵ(orig.)	T ITS–90/K
608.54	1.684	608.500
609.52	1.698	609.480
609.95	1.704	609.910
610.90	1.717	610.860
611.65	1.727	611.610
612.81	1.745	612.770
613.62	1.758	613.580
613.95	1.763	613.910
614.24	1.768	614.200
614.75	1.779	614.710

Region C: one-phase region above 373.12 K

C54Fogo Ref. 54

T/K	ρ/kg.m^{-3}	ϵ(orig.)	T ITS–90/K
649.55	213.6	3.270	649.582
655.65	213.6	3.210	655.681
652.35	229.0	3.290	652.382
658.05	229.0	3.290	658.081
663.75	229.0	3.250	663.780
668.75	229.0	3.250	668.779
650.55	261.3	4.160	650.582
656.65	261.3	4.160	656.681
662.65	261.3	4.120	662.680
668.75	261.3	4.050	668.779
651.35	286.5	4.180	651.382
656.75	286.5	4.180	656.781
661.85	286.5	4.160	661.880
666.75	286.5	4.120	666.779
650.55	300.8	4.940	650.582
655.65	300.8	4.890	655.682
661.65	300.8	4.860	661.680
666.75	300.8	4.830	666.779
651.15	334.3	5.680	651.182
656.65	334.3	5.620	656.681
661.95	334.3	5.620	661.980
665.75	334.3	5.610	666.779
649.55	344.3	6.170	649.582
655.75	344.3	6.130	655.782
661.65	344.3	6.060	661.680
665.75	344.3	5.930	665.779
650.55	402.0	7.180	650.582
656.35	402.0	7.090	656.381
660.95	402.0	6.940	660.980
666.35	402.0	6.940	666.379
637.15	503.1	10.100	637.184
638.55	503.1	10.120	638.584
647.05	503.1	9.980	647.082

C63Gier Ref. 62

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
473.15	1.52	34.6	473.153
473.15	40.53	35.6	473.153
473.15	81.06	36.8	473.153
473.15	121.59	37.9	473.153
473.15	162.12	39.0	473.153

Region C: one-phase region above 373.12 K — Continued

C63Gier Ref. 62 — Continued

T/K	*p*/MPa	ε(orig.)	*T* ITS–90/K
523.15	3.95	26.5	523.171
523.15	40.53	28.2	523.171
523.15	81.06	30.1	523.171
523.15	121.59	32.0	523.171
523.15	162.12	33.9	523.171
523.15	202.65	35.7	523.171
574.15	8.71	19.6	574.183
574.15	40.53	21.2	574.183
574.15	81.06	23.1	574.183
574.15	121.59	25.1	574.183
574.15	162.12	27.0	574.183
574.15	202.65	29.0	574.183
623.15	16.62	12.6	623.186
623.15	40.53	13.9	623.186
623.15	81.06	15.9	623.186
623.15	121.59	18.0	623.186
623.15	162.12	20.0	623.186

C69Hege Ref. 41

T/K	*p*/MPa	ε(orig.)	*T* *ITS*–90/K
473.15	5	34.60	473.150
473.15	25	35.40	473.150
473.15	50	36.35	473.150
473.15	100	38.00	473.150
473.15	150	39.50	473.150
473.15	200	40.80	473.150
473.15	250	41.90	473.150
473.15	300	42.80	473.150
473.15	350	43.70	473.150
473.15	400	44.45	473.150
473.15	450	45.20	473.150
473.15	500	45.80	473.150
523.15	5	26.70	523.170
523.15	25	28.05	523.170
523.15	50	29.40	523.170
523.15	75	30.45	523.170
523.15	100	31.35	523.170
523.15	150	32.80	523.170
523.15	200	34.05	523.170
523.15	250	35.10	523.170
523.15	300	36.00	523.170
523.15	350	36.80	523.170
523.15	400	37.50	523.170
523.15	450	38.20	523.170
523.15	500	38.70	523.170
573.15	10	20.20	573.180
573.15	25	21.50	573.180
573.15	50	23.00	573.180
573.15	75	24.20	573.180
573.15	100	25.30	573.180
573.15	150	27.00	573.180
573.15	200	28.40	573.180
573.15	250	29.50	573.180
573.15	300	30.45	573.180
573.15	350	31.30	573.180
573.15	400	32.00	573.180
573.15	450	32.65	573.180
573.15	500	33.20	573.180
623.15	17	13.10	623.189
623.15	25	14.80	623.189

Region C: one-phase region above 373.12 K

C69Hege Ref. 41 — Continued

T/K	*p*/MPa	ε(orig.)	*T* *ITS*–90/K
623.15	50	17.65	623.189
623.15	75	19.30	623.189
623.15	100	20.50	623.189
623.15	150	22.40	623.189
623.15	200	23.80	623.189
623.15	250	24.90	623.189
623.15	300	25.90	623.189
623.15	350	26.70	623.189
623.15	400	27.35	623.189
623.15	450	28.00	623.189
623.15	500	28.50	623.189
673.15	20	1.85	673.182
673.15	25	2.70	673.182
673.15	30	6.00	673.182
673.15	35	9.25	673.182
673.15	40	10.80	673.182
673.15	50	12.50	673.182
673.15	75	14.90	673.182
673.15	100	16.50	673.182
673.15	150	18.65	673.182
673.15	200	20.00	673.182
673.15	250	21.10	673.182
673.15	300	22.05	673.182
673.15	350	22.85	673.182
673.15	400	23.50	673.182
673.15	450	24.10	673.182
673.15	500	24.60	673.182
723.15	25	1.90	723.159
723.15	35	3.00	723.159
723.15	50	6.50	723.159
723.15	75	10.15	723.159
723.15	100	12.50	723.159
723.15	150	14.95	723.159
723.15	200	16.55	723.159
723.15	250	17.70	723.159
723.15	300	18.70	723.159
723.15	350	19.50	723.159
723.15	400	20.25	723.159
723.15	450	20.90	723.159
723.15	500	21.45	723.159
773.15	25	1.70	773.150
773.15	50	3.70	773.150
773.15	75	7.00	773.150
773.15	100	9.30	773.150
773.15	150	12.00	773.150
773.15	200	13.80	773.150
773.15	250	15.05	773.150
773.15	300	16.10	773.150
773.15	350	16.95	773.150
773.15	400	17.65	773.150
773.15	450	18.30	773.150
773.15	500	18.80	773.150
823.15	25	1.50	823.152
823.15	50	2.65	823.152
823.15	75	4.90	823.152
823.15	100	6.95	823.152
823.15	150	9.85	823.152
823.15	200	11.60	823.152
823.15	250	12.85	823.152
823.15	300	13.90	823.152
823.15	350	14.75	823.152
823.15	400	15.45	823.152

Region C: one-phase region above 373.12 K — Continued

C69Hege Ref. 41 — Continued

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
823.15	450	16.05	823.152
823.15	500	16.60	823.152

C75Luka Ref. 55

T/K	ρ/kg.m^{-3}	ϵ(orig.)	T ITS–90/K
673.15	80	1.58	673.102
673.15	100	1.75	673.102
673.15	120	1.96	673.102
673.15	160	2.32	673.102
673.15	200	2.90	673.102
673.15	240	3.41	673.102
673.15	280	4.12	673.102
673.15	300	4.46	673.102
673.15	350	6.02	673.102
673.15	400	8.02	673.102
773.15	80	1.50	773.071
773.15	100	1.61	773.071
773.15	120	1.71	773.071
773.15	160	2.01	773.071
773.15	200	2.46	773.071
773.15	240	2.92	773.071
773.15	280	3.45	773.071
773.15	300	3.81	773.071
873.15	80	1.39	873.035
873.15	100	1.45	873.035
873.15	120	1.55	873.035
873.15	160	1.80	873.035
873.15	200	2.13	873.035

C78Golu Ref. 58

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
693	9.0	1.23	693.097
693	12.0	1.31	693.097
693	15.0	1.39	693.097
693	18.0	1.53	693.097
693	18.6	1.56	693.097
693	19.2	1.59	693.097
693	19.8	1.62	693.097
693	20.4	1.63	693.097
693	21.0	1.65	693.097
693	21.6	1.74	693.097
693	22.2	1.78	693.097
693	23.4	1.86	693.097
693	24.0	1.92	693.097
693	24.6	2.01	693.097
693	25.2	2.02	693.097
693	25.8	2.14	693.097
693	27.6	2.27	693.097
693	28.2	2.34	693.097
743	12.5	1.25	743.082
743	14.6	1.28	743.082
743	16.3	1.35	743.082
743	18.0	1.33	743.082
743	20.1	1.46	743.082
743	22.1	1.51	743.082
743	24.2	1.60	743.082
743	26.9	1.73	743.082

Region C: one-phase region above 373.12 K — Continued

C78Golu Ref. 58 — Continued

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
743	28.4	1.81	743.082
743	30.1	1.92	743.082
743	31.8	2.03	743.082
743	33.6	2.17	743.082
743	35.2	2.34	743.082
743	38.1	2.68	743.082
783	11.9	1.21	783.067
783	13.8	1.25	783.067
783	15.6	1.28	783.067
783	17.9	1.33	783.067
783	19.3	1.37	783.067
783	21.6	1.42	783.067
783	22.9	1.46	783.067
783	23.7	1.48	783.067
783	24.4	1.51	783.067
783	24.8	1.53	783.067
783	26.4	1.57	783.067
783	27.0	1.59	783.067
783	28.6	1.65	783.067
783	28.8	1.67	783.067
783	29.7	1.70	783.067
783	39.0	1.72	783.067
783	31.5	1.78	783.067
783	32.0	1.80	783.067
783	33.1	1.88	783.067
783	34.2	1.91	783.067
783	36.4	2.02	783.067
783	37.4	2.10	783.067
783	37.6	2.12	783.067
783	38.4	2.17	783.067
783	39.7	2.25	783.067

C81Luka Ref. 47

T/K	ρ/kg.m^{-3}	ϵ(orig.)	T ITS–90/K
621	50	1.351	621.109
675	50	1.312	675.102
675	100	1.717	675.102
675	150	2.245	675.102
675	200	2.853	675.102
675	250	3.605	675.102
675	300	4.572	675.102
675	400	7.011	675.102
675	500	9.699	675.102
675	600	12.745	675.102
726	50	1.296	726.088
726	100	1.676	726.088
726	150	2.164	726.088
726	200	2.731	726.088
726	250	3.441	726.088
726	300	4.282	726.088
726	400	6.515	726.088
726	500	9.055	726.088
726	600	11.961	726.088
778	50	1.260	778.069
778	100	1.634	778.069
778	150	2.083	778.069
778	200	2.605	778.069
778	250	3.280	778.069
778	300	4.061	778.069
778	400	6.011	778.069

Region C: one-phase region above 373.12 K — Continued

C81Luka Ref. 47 — Continued

T/K	ρ/kg.m^{-3}	ϵ(orig.)	*T* ITS–90/K
778	500	8.381	778.069
778	600	11.112	778.069
826	50	1.247	826.051
826	100	1.577	826.051
826	150	2.007	826.051
826	200	2.502	826.051
826	250	3.131	826.051
826	300	3.850	826.051
826	400	5.612	826.051
826	500	8.001	826.051
826	600	10.481	826.051
871	50	1.229	871.036
871	100	1.552	871.036
871	150	1.937	871.036
871	200	2.447	871.036
871	250	3.021	871.036
871	300	3.722	871.036
871	400	5.401	871.036
871	500	7.621	871.036
673	50	1.330	673.102
673	100	1.790	673.102
673	150	2.300	673.102
673	200	2.920	673.102
673	250	3.770	673.102
673	300	4.650	673.102
673	400	7.360	673.102
673	500	9.750	673.102
673	600	13.500	673.102
673	700	16.700	673.102
673	800	20.000	673.102
673	900	24.000	673.102
773	100	1.680	773.071
773	150	2.116	773.071
773	200	2.656	773.071
773	250	3.310	773.071
773	300	4.060	773.071
773	400	6.200	773.071
773	500	8.400	773.071
773	600	11.200	773.071
773	700	14.100	773.071
773	800	17.100	773.071
773	900	19.600	773.071
873	100	1.450	873.035
873	150	1.720	873.035
873	200	2.130	873.035

C84Deul Ref. 44

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
473.15	1.6	34.82	473.110
473.15	5.0	35.00	473.110
473.15	10.0	35.23	473.110
473.15	20.0	35.74	473.110
473.15	30.0	36.19	473.110
473.15	40.0	36.55	473.110
473.15	50.0	36.91	473.110
473.15	60.0	37.31	473.110
473.15	70.0	37.62	473.110
473.15	80.0	37.95	473.110
473.15	90.0	38.27	473.110
473.15	100.0	38.55	473.110

Region C: one-phase region above 373.12 K — Continued

C84Deul Ref. 44 — Continued

T/K	*p*/MPa	ϵ(orig.)	*T* ITS–90/K
473.15	120.0	39.12	473.110
473.15	140.0	39.70	473.110
473.15	150.0	40.00	473.110
473.15	160.0	40.28	473.110
473.15	180.0	40.78	473.110
473.15	200.0	41.28	473.110
473.15	220.0	41.70	473.110
473.15	240.0	42.15	473.110
473.15	250.0	42.39	473.110
473.15	260.0	42.60	473.110
473.15	280.0	43.01	473.110
473.15	300.0	43.40	473.110
573.15	8.6	20.10	573.110
573.15	10.0	20.25	573.110
573.15	20.0	21.05	573.110
573.15	30.0	21.80	573.110
573.15	40.0	22.39	573.110
573.15	50.0	22.92	573.110
573.15	60.0	23.40	573.110
573.15	70.0	23.88	573.110
573.15	80.0	24.29	573.110
573.15	90.0	24.68	573.110
573.15	100.0	25.08	573.110
573.15	120.0	25.77	573.110
573.15	140.0	26.43	573.110
573.15	150.0	26.71	573.110
573.15	160.0	27.04	573.110
573.15	180.0	27.67	573.110
573.15	200.0	28.20	573.110
573.15	220.0	28.65	573.110
573.15	240.0	29.12	573.110
573.15	250.0	29.36	573.110
573.15	260.0	29.60	573.110
573.15	280.0	30.00	573.110
573.15	300.0	30.45	573.110
623.15	17.0	13.10	623.109
623.15	20.0	13.85	623.109
623.15	30.0	15.25	623.109
623.15	40.0	16.26	623.109
623.15	50.0	17.10	623.109
623.15	60.0	17.76	623.109
623.15	70.0	18.33	623.109
623.15	80.0	18.84	623.109
623.15	90.0	19.32	623.109
623.15	100.0	19.75	623.109
623.15	120.0	20.60	623.109
623.15	140.0	21.38	623.109
623.15	150.0	21.74	623.109
623.15	160.0	22.10	623.109
623.15	180.0	22.72	623.109
623.15	200.0	23.35	623.109
623.15	220.0	23.85	623.109
623.15	240.0	24.40	623.109
623.15	250.0	24.63	623.109
623.15	260.0	24.85	623.109
623.15	280.0	25.32	623.109
623.15	300.0	25.75	623.109
673.15	37.0	9.50	673.102
673.15	40.0	10.20	673.102
673.15	50.0	11.72	673.102
673.15	60.0	12.80	673.102
673.15	70.0	13.61	673.102
673.15	80.0	14.31	673.102

Region C: one-phase region above 373.12 K — Continued

C84Deul Ref. 44 — Continued

T/K	p/MPa	ϵ(orig.)	T ITS–90/K
673.15	90.0	14.93	673.102
673.15	100.0	15.48	673.102
673.15	120.0	16.40	673.102
673.15	140.0	17.25	673.102
673.15	150.0	17.66	673.102
673.15	160.0	18.02	673.102
673.15	180.0	18.72	673.102
673.15	200.0	19.40	673.102
673.15	220.0	20.00	673.102
673.15	240.0	20.55	673.102
673.15	250.0	20.79	673.102
673.15	260.0	21.00	673.102
673.15	280.0	21.50	673.102
673.15	300.0	21.90	673.102

Region D: supercooled water

D66Rusc.at $p=p_0$ Ref. 39

T/K	ϵ(orig.)	T ITS–90/K	ϵ(corr.)
271.31	88.835	271.310	88.775
268.62	89.953	268.623	89.893
272.77	88.236	272.770	88.176
271.92	88.584	271.920	88.524
271.02	88.949	271.020	88.889
270.11	89.317	270.113	89.257
269.21	89.685	269.213	89.625
268.30	90.065	268.303	90.005
272.46	88.389	272.460	88.329
271.57	88.749	271.570	88.689
270.69	89.116	270.692	89.056
269.79	89.477	269.793	89.417
268.90	89.843	268.903	89.783
268.02	90.212	268.023	90.152

Region D: supercooled water — Continued

D76Hast.at $p=p_0$ Ref. 64

T/K	ϵ(orig.)	T ITS–90/K
238.15	107.7	238.157
243.15	104.2	243.156
248.15	100.8	248.155
253.15	98.3	253.154
258.15	95.6	258.153
263.15	93.4	263.152
268.15	90.9	268.151

D78Hodg.at $p=p_0$ Ref. 65

T/K	ϵ(orig.)	T ITS–90/K
238.15	106.3	238.157
244.35	101.5	244.356
250.85	98.1	250.855
251.75	98.0	251.755
257.15	95.1	257.154
263.35	92.4	263.352

D82Bert.at $p=p_0$ Ref. 43

T/K	ϵ(orig.)	T ITS–90/K
272.45	88.0	272.450
270.10	89.0	270.101
267.05	90.4	267.051
264.35	91.6	264.352
261.55	92.7	261.553
256.90	94.8	256.904