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Viscosity of Water Substance—New International Formulation and Its Background

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The paper traces the development of our knowledge of the viscosity of water and steam over the last decade, that is over the period of intense experimental and analytic activity which separates the promulgation of the 1964 Supplementary Release on Transport Properties of the Sixth ICPS from the recently announced Release on Dynamic Viscosity of Water Substance. As a result of this work, which was largely stimulated by the activities of the International Association for the Properties of Steam, the new internationally recognized skeleton table and the internationally recommended interpolation equations cover the wide range of pressures and temperatures of 0–100 MPa and 0–800 °C.

Key words: Critically evaluated data; International Formulation; steam; viscosity of water and steam; water.

1. Introduction

In 1964, the Sixth International Conference on the Properties of Steam (ICPS) adopted the first, in its history, skeleton tables for the viscosity and thermal conductivity of water substance. The recommended values embodied in the skeleton tables resulted from years of effort on the part of the world's experts in the subject [1] [1]. The background on which these recommendations were based was described in a paper by Kestin and Whitelaw [2].

The preceding first skeleton table (1964 ST) represented the best knowledge available at the time; it also became a guiding and stimulating standard for the succeeding generation of researchers. During the interval of time that elapsed since 1964 a considerable quantity of new experimental data has been published. These have been critically evaluated and correlated by several teams that worked in cooperation with the International Association for the Properties of Steam (IAPS) formed in 1968. A scrutiny of this work convinces us that progress since 1964 has been remarkable. In particular, as new data appeared, it became clear that the 1964 ST contained considerable errors. Moreover, the blank spaces left in them could now be filled. Finally, the range of pressures and temperatures could be extended and the "tolerances", indicative of uncertainties of the measurements, could be reduced.

The Eighth ICPS held in France in 1974 resolved that the 1964 ST have become obsolete [3] and should be replaced by a revised and updated version. The Conference created a Special Committee [2] with Professor J.

Kestin, IAPS President 1974–1976, as its convenor, and entrusted it with the task of completing new representations of the viscosity and thermal conductivity of water substance and of presenting them to the scientific and engineering community as internationally approved standards. The Committee met twice in 1975, first in Schliersee, Germany, and later in Ottawa, Canada, and adopted final recommendations concerning viscosity. The work on thermal conductivity is still in progress.

These final recommendations were duly circulated among the national delegations represented at the 8th ICPS and approved in 1976 by mail ballot. They are now embodied in an official document entitled Release on Dynamic Viscosity of Water Substance which was circulated among a large number of technical journals of the world. Thus, these recommendations have officially acquired the status of an international standard, in the same way as the 1963 Skeleton Tables of equilibrium properties, and have rendered the 1964 tables of transport properties devoid of this status.

The Release is given verbatim in its officially approved form as Appendix I in this paper. The remainder of the paper describes the present state of our knowledge concerning the viscosity of water substance and gives details of the trends of thought that guided the Special Committee in its work of formulating the preceding document.

2. Progress Achieved since 1964

2.1. General Remarks

Tables 1a–d list all experimental investigations on the viscosity of water substance that were available to the Special Committee and that were critically examined and analyzed by its members. Table 1e records the experimental work which has been published since the termination of the work that led to the Release (Appendix I) and that could not be taken into consideration any more. The entries have been arranged chronologically and it can

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[1] Numbers in brackets designate literature references.

[2] The Committee consisted of twelve members representing France, the Federal Republic of Germany, Japan, the USA, and the USSR. Their names are listed in Appendix I.

TABLE 1a.　Water, 0 °C–100 °C, atmospheric pressure

First author	Year	Method	Temperature (°C)	Reference
Poiseuille	1840	capillary	0–45	6
Graham	1861	capillary	0–70	7
Sprung	1876	capillary	0–50	9
Grotrian	1879	capillary	8–31	10
Slotte	1883	capillary	0–97	11
Noak	1886	capillary	0–60	12
Thorpe	1894	capillary	0–100	13
Heydeweiller	1896	capillary	21	14
Hosking	1909	capillary	0–100	15
Bingham	1912	capillary	0–97	16
White	1914	capillary		18
Leroux	1925	oscill. cyl.	1–44	19
Geddes	1933	capillary	20–80	20
Wobser	1941	capillary	20	21
Coe	1944	capillary	25–40	22
Hardy	1949	capillary	5–125	23
Hoeppler	1952	fall. body	20	24
Swindells	1952	capillary	20	5
Weber	1955	capillary	0–40	26
Roscoe	1958	oscill. sphere	20	27
Malyarov	1959	capillary	20	34
Caw	1961	capillary	20–30	28
Hallet	1963	capillary	−25–25	29
Korosi	1968	capillary	20–150	30
Korson	1969	capillary	8–70	31
Penn	1971	channel flow	20	32
Marvin	1971		20	33
White	1971	oscill. sphere	20	38
Eicher	1971	capillary	20	35

TABLE 1b.　Water, high pressure

First author	Year	Method	Max. temp. (°C)	Max. pres. (bar)	Reference
Roentgen	1884	capillary	11	29	56
Warburg	1884	capillary	20	150	57
Cohen	1892	capillary	23	912	58
DeHaas	1894	capillary	153	saturated	8
Hauser	1901	capillary	100	405	59
Bridgman	1926	fall. body	75	10790	60
Sigwart	1936	capillary	371	248	61
Timrot	1940	capillary	374	355	97
Hardy	1949	capillary	125	saturated	23
Golubev	1959	capillary	300	784	62
Moszynski	1961	oscil. sphere	186	346	45
Mayinger	1962	capillary	300	765	43
Timrot	1963	capillary	370	492	44
Weber	1963	fall. body	160	490	63
Tanaka	1963	capillary	372	978	52
Bett	1965	fall. body	100	10133	47
Wonham	1966	rotat. cyl.	108	226	64
Horne	1966	roll. ball	20	1961	48
Dudziak	1966	oscill. disk	350	3220	46
Rivkin	1966	capillary	200	50	81
Agayev	1967	capillary	100	1178	50
Agayev	1968	capillary	150	1178	49
Korosi	1968	capillary	150	saturated	30
Nagashima	1968	capillary	372	991	53
Kerimov	1969	capillary	275	1178	51
Rivkin	1970	capillary	375	500	54
Rivkin	1972	capillary		saturated	55
Rivkin	1972	capillary	375	1000	102

TABLE 1c.　Steam, atmospheric pressure

First author	Year	Method	Temperature (°C) (maximum)	Reference
Kundt	1875	oscill. disk	20.6	71
Puluj	1878	oscill. disk	16.7	72
Vogel	1914	oscill. disk	28.9	73
Smith	1924	capillary	263	74
Braune	1930	oscill. disk	407	75
Bonilla	1951	capillary	1450	136
Bonilla	1956	capillary	1200	66
Shifrin	1959	capillary	866	65
Latto	1965	capillary	1071	67
Zhdanov	1968	capillary	630	76
Timrot	1973	oscill. disk		70
Thoen-Hellemans	1973	theoretical		4

TABLE 1d.　Steam, high pressure

First author	Year	Method	Max. temp. (°C)	Max. pres. (bar)	Reference
Speyerer	1925	capillary	347	10	83
Shugayev	1933	capillary	400	94	84
Shiller	1935	nozzle flow	300	30	85
Hawkins	1935	fall. body	540	248	87
Sigwart	1936	capillary	383	264	86
Shugayev	1939	capillary	600	245	88
Hawkins	1940	capillary	538	125	89
Timrot	1940	capillary	601	301	97
Jackson	1949	annular flow	650	101	90
Jackson	1959	annular flow	471	312	91
Kjelland-Fosterud	1959	capillary	540	981	135
Osborne	1959	capillary	482	69	92
Whitelaw	1960	capillary	654	785	98
Kestin	1960	oscill. disk	237	19	78
Moszynski	1961	oscill. disk	267	42	45
Witzell	1961	capillary	315	92	93
Mayinger	1962	capillary	703	608	43
Timrot	1963	capillary	700	495	44
Barnett	1963	annular flow	495	689	99
Tanaka	1963	capillary	907	982	52
Kestin	1963	oscill. disk	275	52	80
Ray	1964	capillary	700	785	101
Jackson	1965	annular flow	550	689	100
Dudziak	1966	oscill. disk	560	3460	46
Rivkin	1966	capillary	250	29	81
Nagashima	1968	capillary	905	1004	53
Sato	1968	capillary (coiled)	223	9	68
Rivkin	1968	capillary	450	354	82
Sato	1970	capillary (coiled)	505	25	69
Rivkin	1970	capillary	395	220	104
Rivkin	1973	capillary			103

TABLE 1e.　Publications after 1974

First author	Year	Region covered	Reference
Rivkin	1974	critical region	112
Nagashima	1974	steam (600 °C, 20 MPa)	96
Mayinger	1976	critical region	137

be verified that about 40% of all papers have been published after 1963, the cut-off year for the 1964 tables. These data not only cover an extensive range of pressure and temperature, but are also indicative of major improvements in experimental technique.

The tables summarize exclusively experimental determinations with the only exception a study by Theon-Hellemans and Mason [4] which examines theoretically the thermodynamic consistency between the viscosity and thermal conductivity of low-density steam. At the present time theoretical studies of the viscosity of water substance in all its forms have not led to sufficiently reliable and precise results to merit inclusion. The author hopes that a statistical theory of, for example, dense-steam properties based on an improved version of Enskog's theory or of near-critical behavior formulated in terms of the recently discovered scaling laws will become possible in the not too distant future.

2.2. Viscosity of Water at Atmospheric Pressure in the Range 0–100 °C

The data listed in table 1a are contained in some thirty reports [5–38]. The viscosity of water at atmospheric pressure of 20 °C is of particular importance because it is often used as a reference and calibration standard.

In 1952, Swindells, Coe, and Godfrey [5] published their data on water at atmospheric pressure at 20 °C measured with a capillary viscometer. Since then their value

$$\mu_{20 \,°C} = (1.0019 \pm 0.0003) \times 10^{-3} \, Pa \cdot s, \qquad (1)$$

(sometimes rounded off to 1.002×10^{-3} Pa·s) has been accepted by many researchers as a calibration standard.

For many years before, the value 1.005×10^{-3} Pa·s had been widely used. Figure 1 graphically describes the

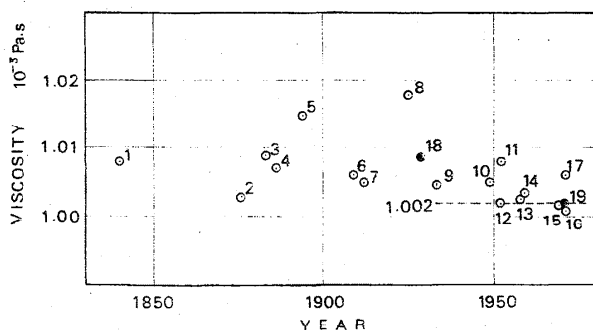FIGURE 1. Chronological variation of the experimental viscosity at 20 °C and atmospheric pressure

1 Poiseuille	11 Hoeppler
2 Sprung	12 Swindells et al.
3 Slotte	13 Roscoe and Bainbridge
4 Noak	14 Malyarov
5 Thorpe and Rodger	15 Kawata et al.
6 Hosking	16 Penn and Kearsley
7 Bingham and White	17 White and Kearsley
8 Leroux	18 International Critical Tables
9 Geddes	19 Table 4
10 Hrady and Cottington	

chronological variation of this value. As was pointed out by Grigull [39], most values published prior to 1950 are higher than (1). In later years, Roscoe and Bainbridge [27] measured

$$\mu_{20 \,°C} = (1.0025 \pm 0.0005) \times 10^{-3} \, Pa \cdot s, \qquad (2)$$

in an oscillating-sphere apparatus, and Malyarov [34] reported

$$\mu_{20 \,°C} = (1.0035 \pm 0.0003) \times 10^{-3} \, Pa \cdot s, \qquad (3)$$

as a result of his measurements in a capillary apparatus. It is seen that the discrepancies between these most carefully measured values exceed the experimental uncertainties claimed by their authors. No convincing resolution of this dilemma has been offered so far.

One of the major corrections that can be suspected as the cause of the preceding state of affairs [40] is the inlet-length correction (otherwise known as the kinetic-energy correction). Kawata et al. [36] indirectly confirmed Swindell's value by the step-up method, that is by comparing the viscosity of water with that of a more viscous oil. It is, namely, possible to use the falling-ball method to perform an absolute measurement of the viscosity of a moderately viscous oil with a negligible non-Newtonian behavior. Similarly, the contribution of the inlet-length correction can be minimized when measurements are made in a capillary viscometer. These circumstances allowed Kawata, in his opinion, to check for unknown, systematic errors of the capillary method.[3] Kestin and Whitelaw [37] and Caw and Wylie [28] found that the effects of dissolved air and of pressure cycles, sometimes blamed for these discrepancies, are not, in fact, significant.

The likelihood of the existence of an unappreciated systematic error was recently studied by a group at NBS who employed the channel-flow method [38] as well as the oscillating method [32]. The results were summarized by Marvin [33] who recommended that Swindell's value (1) should be retained with the proviso that its uncertainty should be increased to 0.25%.

A theoretical analysis and review of the inlet-length correction problem was recently given by Kestin, Sokolov, and Wakeham [41]. In the author's opinion this successfully concludes half a century of discussion concerning the dependence of the inlet-length correction on the Reynolds number.

Judging by the written fact, Swindell's work is a most careful and convincing study. In the author's judgement this is still the best determination of the viscosity of water at 20 °C.

The influence of temperature on the viscosity of water at atmospheric pressure described in a number of recent determinations [30, 31, 35] shows very good agreement if judged by the values of the ratio $\mu(t \,°C)/\mu(20 \,°C)$. Since the viscosity equation for atmospheric water covering a wide range of temperature and pressure is neces-

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[3] An element of doubt remained owing to an uncertainty of 0.25% in his empirically determined correction for the wall effect; this induces a residual uncertainty of 0.06% in the viscosity itself.

sarily complex, it is convenient to employ simpler forms in the restricted range 0–100 °C at atmospheric pressure. Here it is useful to mention the equations proposed by Eicher [35], and Ikeda and Nagashima [42]. The latter (of a modified Arrhenius type), and its output, are given in Appendix II. The diagram in figure 2 contains the corresponding deviation plot. As the ice-point temperature of 0 °C is approached, the temperature dependence becomes more pronounced and the data for supercooled water due to Hallet [29] and Eicher [35] are helpful for the determination of the value of water at 0 °C and atmospheric pressure when it exists in equilibrium with ice. Similarly, data above the steam point are needed to determine the value of the viscosity of water at 100 °C and atmospheric pressure when it exists in equilibrium with its vapor. The only data available above 100 °C are those by de Haas [8], Hardy and Cottington [23] and Korosi [30].

2.3. Viscosity of Water under High Pressure

Systematic measurements of the viscosity of water under high pressure were carried out by Mayinger [43], Timrot and Khlopkina [44], Moszynski [45], Dudziak and Franck [46], Bett and Cappi [47], Horne and Johnson [48], and Agayev and co-workers [49–51]. The work of Tanaka and co-workers [52], Nagashima and Tanishita [53] and Rivkin and co-workers [54, 55, 102] was carried out under high pressure as well as high temperature. Of all these, only references [43, 44, and 45] were available in 1964.

Dudziak and Franck [46] covered the wide range of up to 560 °C and 350 MPa with the aid of the oscillating-disk method but with a somewhat less satisfactory reproductibility. The data in [47] and [48] are given in terms of temperature and density rather than pressure and are, therefore, inconvenient as material for a precise analysis. Reference [45] was used as one of the few primary

sources for the 1964 ST, but at 100 °C it gave values which were lower than indicated by the most recent measurements.

The most extensive and precise set of data on water is contained in [49–51] and covers a temperature range 0–270 °C with pressures up to 120 MPa. These measurements indicate that the initial pressure derivative along an isotherm changes sign from negative to positive at about 32 °C, confirming older estimations.

Above 300 °C there exist two sets of systematic measurements, namely [53] with an estimated precision of 2–3% and [54, 55, 102] with one of 1%. The two sets show mutual deviations of 2–5% in this range even though they enjoy much closer agreement in the steam region.

The older data of [56–62], as well as the more recent data of [63, 64] do not, in the writer's opinion, enjoy comparable credibility.

2.4. Viscosity of Steam at Atmospheric Pressure

In 1964 there existed only two sets of measurements of the viscosity of steam at atmospheric pressure in a wide range of temperatures, namely those of Shifrin [65] and Bonilla, Wang, and Weiner [66]. The sets have a systematic, mutual deviation reaching 4% and the 1964 ST compromised with the linear equation of Shifrin [65]. The more recent measurements of Latto [67], Sato and co-workers (extrapolated) [68, 69] and Timrot and co-workers [70] agreed with the 1964 ST within their quoted experimental error. However, especially at high temperatures, the situation has not improved much since 1964. The more precise values of [68–70] are restricted to a maximum temperature of 505 °C, while the most extensive measurements [67] cover the range up to 1100 °C albeit with scattered deviations of up to 2% with respect to the paper's own correlation.

The capillary method was used in most measurements except for [70] in which the oscillating disk was em-
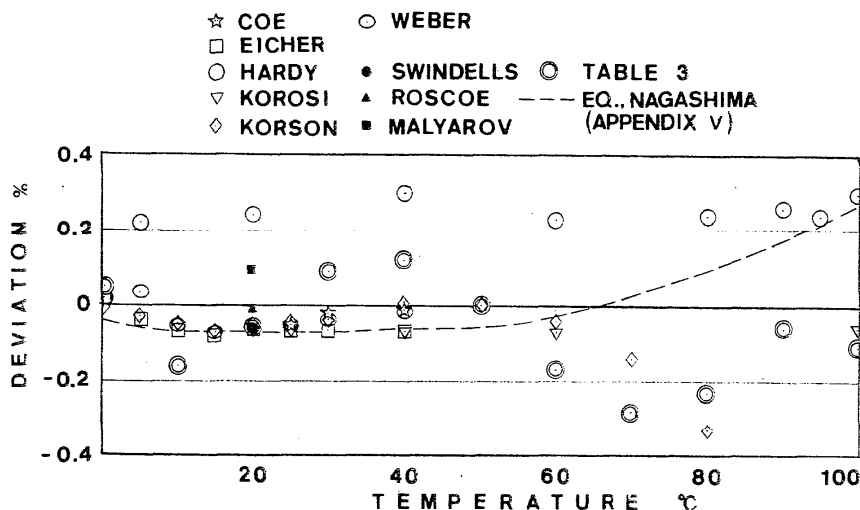

FIGURE 2. Deviations of experimental data from equation (6)—water at atmospheric pressure

ployed. Additional, but less significant measurements [71–76, 136] are also available in the range under discussion.

In the region of combined high pressure and high temperature direct experimental determinations become very difficult to perform. One alternative is to attempt to make calculations based on Enskog's theory for hard spheres and to relate them to accurate values of the viscosity μ_0 extrapolated to zero density. Without any essential loss, the latter can be replaced by the viscosity μ_1 at atmospheric pressure. Calculations of this value, such as for example Krieger's [77], agree fairly well with experimental data but cannot, really, substitute for them.

Reliable values of μ_0 (or μ_1) can play a role in the estimation of the realiability of thermal conductivity, as proposed by Thoen-Hellemans and Mason.

2.5. Negative Pressure Effect on the Viscosity of Steam

The existence of a negative effect of pressure on the viscosity of steam at subcritical temperatures was first discovered in 1960 by Kestin and Wang [78][4] and confirmed by later measurements in the same oscillating-disk instrument [45, 80]. These data were fully taken into account in the formulation of the 1964 ST. All doubts concerning the existence of this effect have been decisively dispelled by later investigators who employed an alternative method. Rivkin and co-workers [81, 82] covered the range up to 450 °C in a closed-circuit capillary viscometer, while Sato et al. [68, 69] used a once-through capillary viscometer. Both sets of measurements showed very good agreement with the data obtained at Brown University.

There exist many older measurements [83–93] which failed to identify the negative effect. Some were in error due to unsuitable flow conditions, such as excessively large Reynolds numbers in falling-body viscometer, failure to eliminate turbulence in a nozzle viscometer or of secondary flow in coiled-capillary instruments.

Barua and Gupta [94] made an attempt theoretically to calculate the negative pressure effect and hypothesized that it may be due to the formation of clusters of H_2O molecules. An analogous negative pressure effect was recently discovered in D_2O by Abe and Nagashima [95].

Many gases of simple molecules approximately follow the common rule that the viscosity excess

$$\Delta\mu = \mu(T, \rho) - \mu_0(T, 0), \qquad (4)$$

can be expressed as a function of density alone, μ_0 denoting the value of viscosity extrapolated to zero density isothermally. The 1964 ST adopted this rule for steam in the temperature range 375–700 °C, but some grid points along the near-critical 350 °C isotherm were left blank due to the lack of reliable experimental data and to a suspected critical anomaly.

Recent measurements show that the rule embodied in (4) is inadequate for steam even as an approximation,

particularly along the 375 °C isotherm. Nagashima, Murai, and Tanishita [96] measured the pressure dependence of the viscosity of steam starting with 250 °C where the negative pressure effect is significant and showed that (4) led to an acceptable approximation, that is one within the experimental error, only at temperatures above 600 °C.

The variation of the derivative

$$(\partial\mu/\partial P)_T$$

with temperature has been plotted in figure 3. The broken line corresponds to the hypothesis that the viscosity excess is a sole function of density.

2.6. Viscosity of Steam under High Pressure in the Range 375–500 °C

In this region, the 1964 ST was constructed on the basis of the hypothesis that the excess viscosity was a function of density alone. The data used were those of Timrot [97], Timrot and Khlopkina [44], Whitelaw [98] and Mayinger [43]. The other data found in the literature, including [99, 100] and [135], were considered less reliable. The measurements obtained in 1964 by Tanaka and co-workers [52] and in 1965 by Ray [101] are very close to the values in the 1964 ST. However, later measurements, namely those of Nagashima et al. [53] and of Rivkin et al. [82, 103, 104] published during the period 1968–1974 showed considerable deviations. For example, the maximum discrepancy in the range 20 MPa to 40 MPa was three times larger than the already large tabular tolerance (i.e. 13%). A look at figure 4 which plots the deviations of the data in [43, 44, 52, 97, 101] from equation (6) reveals the existence of systematic departures from the data of refs. [53, 82, 98, 102, 103, and 104] seen represented graphically in figure 5. The origin of such systematic differences could be attributed, as was suggested in [53] and [105], to the presence of unsuitable flow conditions in the instruments. In this range the kinematic viscosity is low and the flow can easily turn turbulent, especially in the metallic capillaries used in these references, given that the internal walls cannot be made satisfactorily smooth. Under such condi-
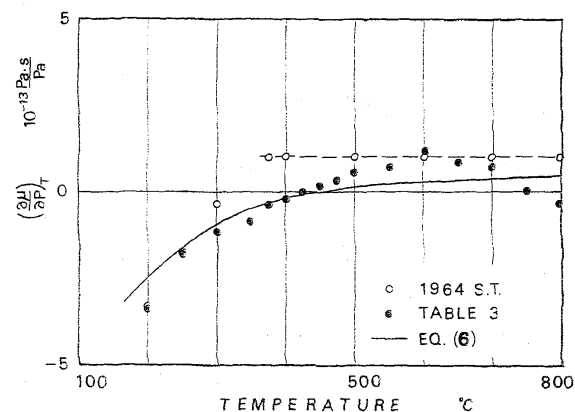

FIGURE 3. Variation of the pressure dependence of the viscosity of steam at 0.1 MPa
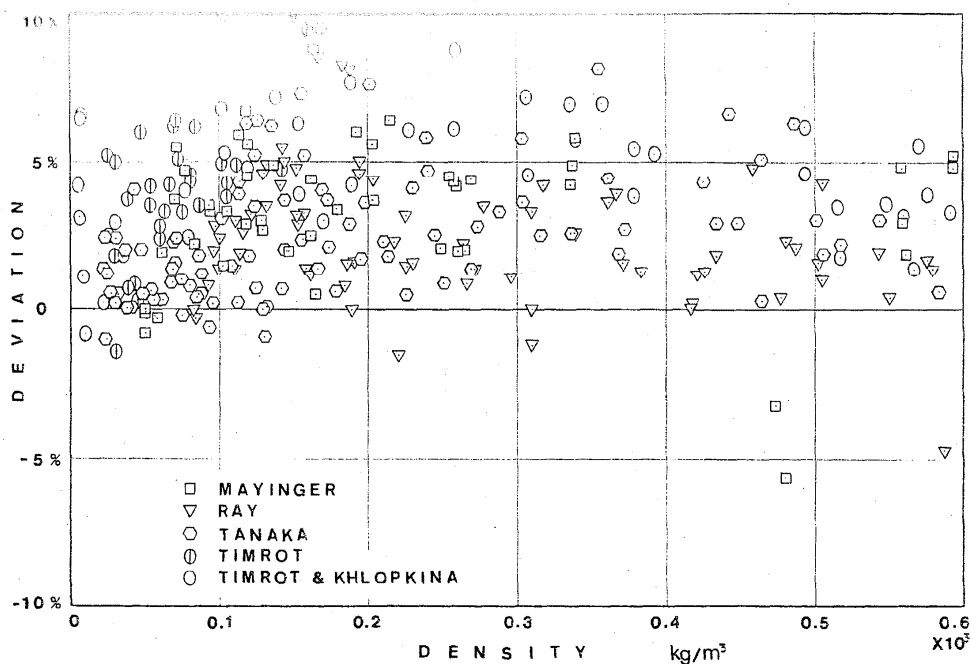
FIGURE 4. Deviation of experimental data from equation (6)—Group I (steam)

tions, the flow can become turbulent at a critical Reynolds number which is considerably lower than the oft-accepted limit of 2300. The authors of references [53, 81, 82, 103, and 104] took extreme care in this respect. Since all of the data mentioned above were obtained in capillary-flow assemblies, future measurements based on another principle, [106], would be helpful. The only data obtained in

an oscillating-disk instrument, [46], are not sufficiently precise to throw light on this problem.

Experimental data are available up to 900 °C, [52, 53]; their existence made it possible to extend the limits of pressure and temperature in the new IAPS representation from the 700 °C and 80 MPa of the 1964 ST to the present 800 °C and 100 MPa.
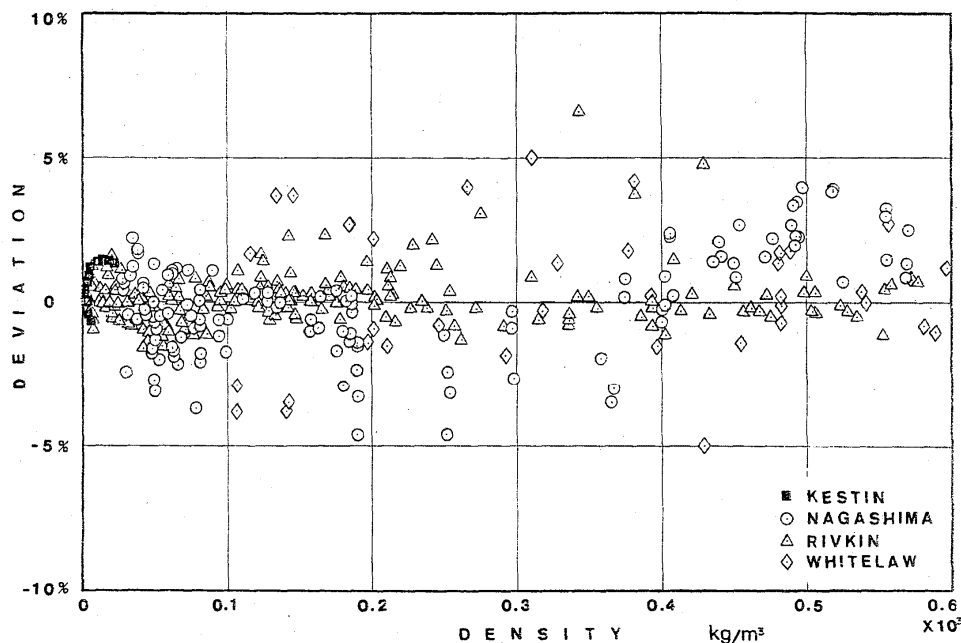

FIGURE 5. Deviation of experimental data from equation (6)—Group II (steam)

2.7. Viscosity of Water and Steam in the Critical Region

The existence of the so-called critical anomaly has been experimentally confirmed in recent years with respect to a range of properties and substances. The preceding term describes the departures from classical behavior of the real properties of substances in a smaller or larger region encompassing the critical point. The critical anomaly in viscosity is expected to be a weak one [107] as evidenced in experiments in CO_2 [108, 109], ethylene [110] and several other substances [111].

The only measurements of the critical anomaly in the viscosity of steam are those by Rivkin et al. [112] who employed a capillary viscometer. The results of these measurements are shown in figure 6. Measurements in the critical region can easily be falsified by a choice of the wrong method. As far as viscosity is concerned, measurements with an oscillating disk enjoy a distinct advantage over the transpiration method. The results can further be considerably falsified by the improper selection of the equations of state, critical constants and temperature scale. When the transpiration method is used the instrument measures, essentially, the kinematic viscosity; this means that an error in density enters directly into that of the dynamic viscosity. Furthermore, it now becomes essential

to account for the variation in density along the flow path. In this connection it is worth realizing that the difference between the density calculated at the same near-critical point with the aid of 1967 IFC formulation [113] and the 1968 IFC formulation [114], both extensively used throughout the world, can reach as much as 4.5% as is the case at 375 °C and $\rho/\rho_c = 0.89$. Similarly, the inherent difference in temperature scales between the IPTS–48 and IPTS–68 induces a difference of 0.6% in the calculated density at 375.6 °C and 23 MPa. Finally, one must not forget that the two formulations stipulate different critical constants.

The critical anomaly in the PVT relation should be taken into account when viscosity measurements in the near-critical region are being evaluated. At present, the situation is unclear and a meaningful analysis of the critical anomaly in the viscosity of steam had better be left for the future.

2.8. Viscosity of Water and Steam along the Saturation Line

The data available at the time when the 1964 ST were established were insufficient to define the values of the viscosity of saturated water and steam. Particularly scarce
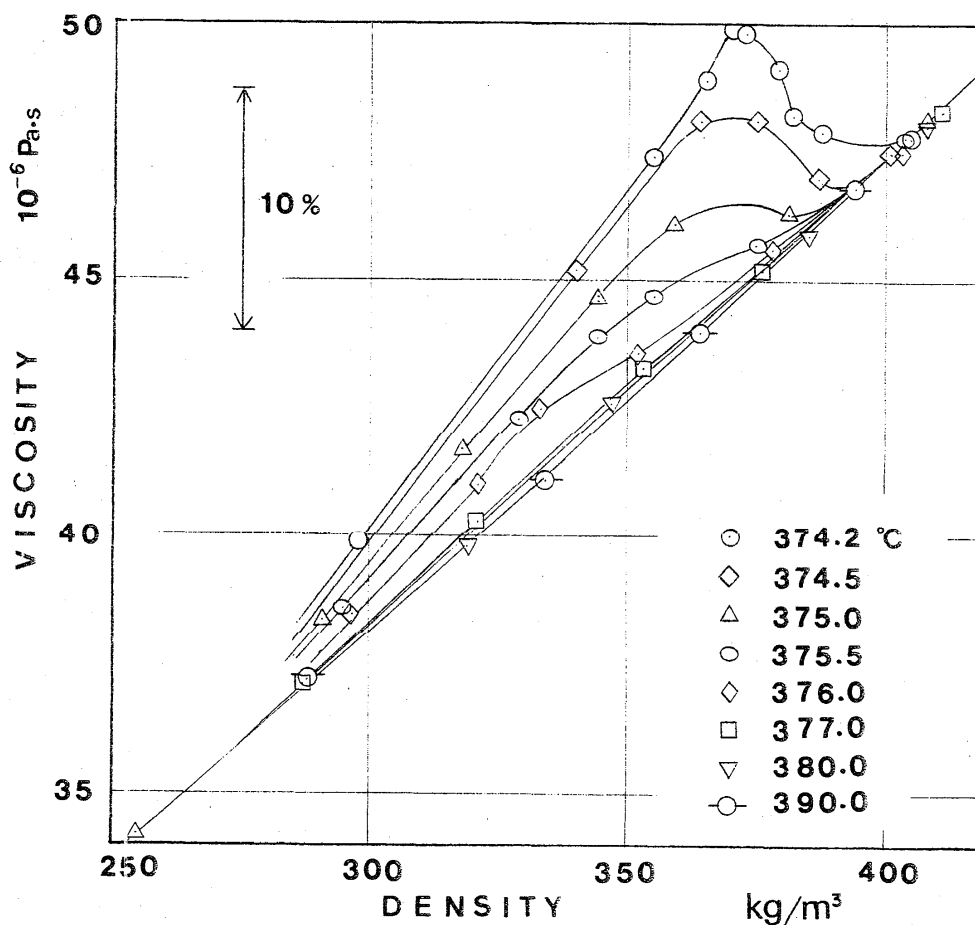
FIGURE 6. Rivkin's data in the critical region

were the data on saturated water. For this reason, the 1964 ST made no recommendations for the values along the saturation line.

In 1968 Nagashima et al. [53] obtained experimental data which were much lower than the values estimated previously by Bruges et al. [115] and exhibited a steep rate of decrease along isotherms on the water side as the saturation line was approached. This was particularly pronounced, for example, along the 370 °C isotherm. This tendency was later confirmed by the precise investigations of Rivkin and coworkers [54, 104] into the viscosity of saturated water and steam at higher temperatures. Precise values for saturated steam below 100 °C can now be extracted from more recent data at lower pressures [70]. Older data in this region, [71–73], obtained in an oscillating-disk apparatus are not as reliable as those due to Timrot et al. [70].

The correlating equation given in the Release (Appendix I) can be used right up to the saturation line on both sides. Table 6 gives the corresponding output.

2.9. Equations for Water and Steam

Since 1964 numerous investigators published correlating equations for the viscosity of water substance covering a wide range of pressures and temperatures. Here we may mention Sato and Minamiyama [116], Tanaka et al. [52], Bruges et al. [115], Rivkin [117], Miyabe and Nishikawa [118], Bruges and Gibson [119], Grigull et al. [120], Tanishita et al. [121], Stein [122], Nagashima et al. [53, 123], Kesselman et al. [124, 125], Lukas [126], Mamedov et al. [127] and Rivkin et al. [128]. Many of these equations served merely to interpolate the 1964 ST and were not suitable to encompass the recent data. The equations of [117], [126] and [128] expressed the viscosity as an implicit function of temperature and pressure. A similar idea was employed by Tanishita et al. [123] who correlated the region up to 1000 °C and 350 MPa in terms of temperature and pressure rather than temperature and density. The proposal due to Miyabe and Nishikawa [118] contained the first equation which correlated the entire range of the 1964 ST in terms of temperature and density. The trends represented by the more recent experimental work described in section 2.6 were fully reflected only in a limited number of correlations, among them refs. [53, 123] for the steam region and ref. [128] in the water region below 50 °C. From among all those equations it was possible to select only two, namely the equation due to Nagashima, Ikeda and Tanishita [129] on the one hand, and that proposed by Aleksandrov, Ivanov and Matveev [130] on the other, for consideration as candidates for international adoption.

3. New Skeleton Table and Interpolation Equations

3.1. Outline of the Activities of IAPS in the Matter of Compiling and Evaluating Data

The situation concerning experimental data described in section 2 forced upon IAPS the awareness that a revi-

sion of the 1964 ST was inevitable, and the task of achieving it was entrusted to Working Group II. Within its framework, three teams, one each in Germany, Japan and the Soviet Union, independently collected and analyzed all available data. Intermediate results as well as criteria for the exercising of scientific judgement were discussed at the April 1973 meeting of the Group in Hanover. The Working Group resolved to recommend to the Eighth International Conference on the Properties of Steam a formal revision of the 1964 ST and an extension of the range to 800 °C and 100 MPa. The question as to whether to favor a new skeleton table or a global correlating equation aroused much controversy. At the next meeting in September 1973 in London two sets of collected data, later designated Available Data, [131] and [132], were produced. These served as a foundation for the selection of

TABLE 2. Primary references of selected experimental data (International Input)

Author	Year	Region	Method	Evaluated precision	Reference
White	1913	1	1	0.5%	18
Coe	1944	1	1	0.3	22
Hardy	1949	1	1	0.5	23
Swindells	1952	1	1	0.1	5
Weber	1955	1	1	0.3	26
Roscoe	1958	1	2	0.1	27
Malyarov	1959	1	1	0.1	34
Hallett	1963	1	1	0.3	29
Korosi	1968	1	1	0.3	30
Korson	1969	1	1	0.3	31
Eicher	1971	1	1	0.3	35
Shifrin	1959	2	1	3	65
Latto	1965	2	1	3	67
Sato (recalc.)	1968/70	2	1	1.5	68, 69
Timrot (recalc.)	1973	2	1	0.4	70
Moszynski	1961	3	2	2	45
Mayinger	1962	3	1	2	43
Tanaka	1965	3	1	2	52
Agayev	1968	3	1	1	49, 50
Nagashima	1968	3	1	2	53
Kerimov	1969	3	1	1	51
Rivkin	1970/72	3	1	1	54, 55, 102
Whitelaw	1960	4	1	4	98
Kestin	1960	4	2		78
Kestin	1963	4	2	0.8	80
Nagashima	1968	4	1	3	53, 96
Sato	1968/70	4	1	1.5	68, 69
Rivkin	68/70/73	4	1	1	81, 82, 102, 104
Timrot	1973	4	1	0.4	70
Whitelaw	1960	5	1	4	98
Mayinger	1962	5	1	3	43
Nagashima	1968	5	1	3	53
Tanaka	1965	5	1	3	52

Region:
1. Water at atmosph. pressure.
2. Steam at atmosph. pressure.
3. Pressurized water.
4. Steam < 550 °C.
5. Steam > 550 °C.

Methods:
1. Capillary flow.
2. Oscillating body or vessel.

primary data on which to base the new international representation. Certain data were deleted or corrected; they are seen listed in Appendix III, and the justification for this action can be found in [133].

The critical evaluation and the selection of a primary set of data together with levels of uncertainty to be associated with them, later designated as the International Input, was completed at the meeting in Moscow in May 1974. This is seen listed in table 2. From these, the teams in Japan, [129], and the USSR, [130], distilled correlating equations as drafts to be considered by IAPS for adoption. The coefficients in them were determined to minimize the weighted sum of the square of differences.[5] The team in Germany worked to deduce a skeleton table directly from experimental data [134].

The Eighth International Conference on the Properties of Steam held at Giens, France in September, 1974, officially announced that the 1964 ST was considered obsolete, and designated a Special Committee for the purpose of finalizing the new representations on the viscosity and on the thermal conductivity. The Special Committee, consisting of representatives of France, the Federal Republic of Germany, Japan, the USA and the USSR, met at Schliersee, Germany, in April, 1975, and came to a final agreement on the new representation of the viscosity of water and steam. This consisted of a skeleton table directly deduced from experimental data and an interpolation equation. Details of the new representation and comparisons with experimental data are given in the following sections.

3.2. Primary Data

The primary references ("International Input") chosen as a basis for the new international correlation are seen listed in table 2 together with their weights. Table 2 is the fruit of almost two years of effort contributed by an international team of experts, IAPS's Working Group II on Transport Properties.

The criteria on which the selection reflected in table 2 was made included the consideration of

(a) the ranges of temperature and pressure adequate for the new representation

(b) the reliability of the measuring method

(c) the scatter in the data

(d) adequacy of the presentation of the data

(e) date of the measurements

(f) sufficiency of the description of the procedure.

Of course, the quality of the measurements was evaluated from many additional points of view, such as the adequacy of the flow conditions, the quality of the design of the apparatus, the author's own error estimate, the influence of possible secondary effects, the magnitude and method of calculation of the correction applied, and so on. All data listed in table 2 were selected after exhaustive discussions and subject to unanimous agreement among the members of the working group.

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[5] Minor differences in approach, described in [129] and [130] in more detail, can be ignored here.

Even though the references which constitute the International Input have been mentioned before, some additional remarks may be helpful. In Region 1 (water at atmospheric pressure) the critical survey given in section 2.2 suggests that only three references, namely [5], [27] and [34] should be retained as an absolute basis, the remaining data being used in the form of the ratio $\mu(t)/\mu(20\ °C)$. Of these, all but one used the capillary method. The data published before 1944, except one [18], were discarded.

In the steam region at atmospheric pressure the data in [68, 69, 70, and 80] are thought to be burdened with the least experimental errors; they agree well with each other. References [29, 35] include data for supercooled water.

In the superheated steam region the data by Kestin et al. [78, 80], Sato et al. [68, 69], Whitelaw [98], Nagashima et al. [53] and Rivkin et al. [81, 82, 103, 104] were adjudged reliable. The data by Mayinger [43] and Tanaka et al. [52] for $T > 550\ °C$ were also considered reliable. The other data show systematic deviations from them, as already explained in section 2.6. The data of [43] and [52] for $T_c < T < 550\ °C$ show systematic deviation from those of Nagashima et al. and Rivkin et al. in the subregion where the kinematic viscosity is small. The 1964 ST shows the largest deviation from the recent data precisely in this region. The existence of unfavorable flow conditions can be blamed, as suggested in section 2.6. For this reason, the data in these two references were included only for the liquid state and above 550 °C in the gaseous state.

Except for the region of water at atmospheric pressure, data published after 1964 were retained in view of the degree of progress in measuring technique and theoretical understanding achieved by then.

The body of primary data made it possible to establish the new representation of the viscosity of water and steam. The range could now be extended to 800 °C and 100 MPa, as contrasted with 700 °C and 80 MPa of the 1964 ST. The ranges of these two representations are seen juxtaposed in figure 7. Examples of the trends inherent in the primary data will be given in section 3.5.

3.3. Skeleton Table Deduced from Experimental Data

U. Grigull [39] discussed the general philosophy underlying the process of correlating the selected set of experimental data into a skeleton table and an equation. He pointed out that the equation which might replace the skeleton table must fulfill the following two requirements.

(a) The measurements must be represented without systematic deviations.

(b) The surface defined by the equation must be realistic from the physical point of view.

To this it is necessary to remark that there is only a slender probability that an equation satisfying both criteria can be established. Furthermore, even though the present situation was vastly improved compared with that which existed in 1964, the IAPS Working Group reached
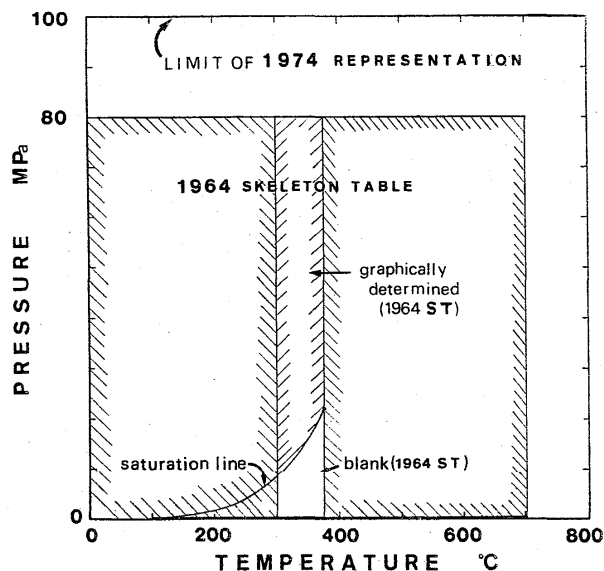
FIGURE 7. Ranges covered by the 1964 S.T. and by the new IAPS representation

the conclusion that the limited reliability of the available experimental data made it impossible to produce a correlation free from systematic departures. For this reason it was decided to deduce the skeleton table directly from the selected data rather than from a smoothed, theoretically reasonable equation.

The final action based on the resolution adopted by the Eighth ICPS consisted of a skeleton table and an interpolation equation; the latter will be discussed in the next section; the method of obtaining the former will be discussed presently.

The skeleton tables, table 3 and 4, are based on the original experimental data of the primary references listed in table 2. The first step was to reduce the data to a standard grid in terms of pressure and temperature. In this manner at each grid point there are generated several alternative values which are then combined into one value by weighted averaging. The reduction of a datum to a predetermined grid node is achieved with the aid of the relation

$$\mu(\rho_0, T_0) = \mu(\mu, T) + [f(\rho_0, T_0) - f(\rho, T)], \quad (5)$$

where ρ_0, T_0, ρ, T are the density and temperature, respectively, at the grid point and at the experimental point. Similarly, the functions $f(\rho_0, T_0)$ and $f(\rho, T)$ represent the viscosity at the grid point and under experimental conditions, respectively; they are calculated with the aid of a first approximation to the interpolation equation, eq (6) of the section following. In applying this procedure it is very important to confine the differences $T-T_0$ and $\rho-\rho_0$ to a very narrow interval. The density was calculated with the aid of the 1967 IFC Formulation [113]. The weighting factors used corresponded to the estimated reliability listed in table 2. Even though the number of data points differs appreciably from reference to reference, no statistical adjustment was made to compensate for these

differences. It is clear that in the present method the adopted value at the grid point tends to be closer to the set of experimental data which contains more individual points if the weighting factors do not differ too much from each other. This is a clear flaw but its remedy is left for future study.

The new skeleton table, table 3, is smooth within the recommended tolerances which are also given in the table. The term "tolerance" here designates the agreed-upon uncertainty and is not related in any direct way to the experimental errors or to the standard deviation.

3.4. Interpolation Equation

The Eighth ICPS adopted the form of the interpolation equation proposed to it by Aleksandrov, Ivanov, and Matveev [130]. The equation given below serves to interpolate the values in table 3 with departures not exceeding the accepted tolerances:

$$\mu = \mu_0 \exp\left[\frac{\rho}{\rho^*} \sum_{i=0}^{5} \sum_{j=0}^{4} b_{ij} \left(\frac{T^*}{T} - 1\right)^i \left(\frac{\rho}{\rho^*} - 1\right)^j\right], \quad (6)$$

where

$$\frac{\mu_0}{\mu\text{Pa} \cdot \text{s}} = \left[\frac{T}{T^*}\right]^{1/2} \left[\sum_{k=0}^{3} a_k \left(\frac{T^*}{T}\right)^k\right]^{-1},$$

μ denotes the dynamic viscosity

ρ denotes density)

T denotes absolute temperature on the 1968 Practical Temperature Scale

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

a_k and b_{ij} are numerical constants.

The adopted values of the constants in eq (6) are given in table 5.

The preceding equation can be used [130] in practice, with reduced reliability, over a wider range of states than originally intended. It can be used to 1000 MPa in the range -20 °C to 100 °C (liquid phase), to 350 MPa between 100 °C and 560 °C and to 100 MPa in the range 560 °C–900 °C. In this manner the viscosity of water and steam has been described over the whole range of interest with the aid of a single equation with temperature and density as its independent variables. Tables 6 and 7 contain smooth values calculated with the aid of this equation. Figures 8 and 9 depict the dependence of viscosity on temperature and pressure, whereas figures 10 and 11 represent the kinematic viscosity. In order to retrieve the same values, it is necessary to calculate the density with the aid of the 1968 IFC Formulation [114] (for calculated specific volumes, see Appendix IV).

The IAPS minutes of its meeting in Schliersee in 1975 as well as the Release, Appendix I, mention the existence of an alternative interpolation equation proposed by Nagashima, Ikeda, and Tanishita [129] which is characterized in Appendix V.

Even though the possible critical anomaly has not been

TABLE 3. Viscosity of water substance—critically evaluated experimental data

Units: t °C, P MPa, μ 10^{-6}Pa·s

P	t						
	0	25	50	75	100	150	200
0.1	1791	891.0	547.1	377.3	12.42	14.29	16.26
	18	8.9	5.5	3.8	0.25	0.29	0.33
0.5	1790	891.2	546.7	378.0	281.7	182.3	16.05
	18	8.9	5.5	3.8	2.8	1.8	0.32
1.0	1789	891.1	546.8	378.2	281.9	182.4	15.92
	18	8.9	5.5	3.8	2.8	1.8	0.32
2.5	1786	890.8	547.1	378.5	283.3	182.8	134.6
	18	8.9	5.5	3.8	2.8	1.8	1.4
5.0	1780	890.3	547.7	379.2	283.1	183.4	135.2
	18	8.9	5.5	3.8	2.8	1.8	1.4
7.5	1774	889.8	548.3	379.8	283.8	184.1	135.9
	18	8.9	5.5	3.8	2.8	1.8	1.4
10.0	1768	889.4	548.7	380.4	284.7	184.7	136.4
	18	8.9	5.5	3.8	2.9	1.9	1.4
12.5	1762	889.1	549.1	381.0	285.3	185.3	137.0
	18	8.9	5.5	3.8	2.9	1.9	1.4
15.0	1756	888.7	549.5	381.6	286.0	186.0	137.6
	18	8.9	5.5	3.8	2.9	1.9	1.4
17.5	1750	888.5	550.0	382.3	286.7	186.9	138.2
	18	8.9	5.5	3.8	2.9	1.9	1.4
20.0	1744	888.2	550.4	382.9	287.4	187.3	138.8
	17	8.9	5.5	3.8	2.9	1.9	1.4
22.5	1738	887.9	550.9	383.5	288.0	187.9	138.4
	17	8.9	5.5	3.8	2.9	1.9	1.4
25.0	1733	887.6	551.3	384.2	288.7	188.5	140.0
	17	8.9	5.5	3.8	2.9	1.9	1.4
27.5	1728	887.4	551.8	384.8	289.4	189.1	140.6
	17	8.9	5.5	3.9	2.9	1.9	1.4
30.0	1723	887.2	552.3	385.5	290.0	189.8	141.2
	17	8.9	5.5	3.9	2.9	1.9	1.4
35.0	1713	886.8	553.3	386.7	291.4	191.0	142.3
	17	8.9	5.5	3.9	2.9	1.9	1.4
40.0	1705	886.6	554.3	388.0	292.7	192.2	143.5
	17	8.9	5.5	3.9	2.9	1.9	1.4
45.0	1697	886.5	555.3	389.3	294.0	193.4	144.6
	17	8.9	5.6	3.9	2.9	1.9	1.5
50.0	1690	886.4	556.3	390.6	295.4	194.6	145.8
	17	8.9	5.6	3.9	3.0	2.0	1.5
55.0	1684	886.5	557.4	392.0	296.7	195.8	146.9
	17	8.9	5.6	3.9	3.0	2.0	1.5
60.0	1679	886.7	558.5	393.3	298.0	197.0	148.0
	17	8.9	5.6	3.9	3.0	2.0	1.5
65.0	1674	886.9	559.7	394.6	299.4	198.2	149.0
	17	8.9	5.6	4.0	3.0	2.0	1.5
70.0	1670	887.3	560.9	395.9	300.7	199.4	150.1
	17	8.9	5.6	4.0	3.0	2.0	1.5
75.0	1666	887.7	562.0	397.3	302.0	200.6	151.2
	17	8.9	5.6	4.0	3.0	2.0	1.5
80.0	1662	888.3	563.3	398.6	303.4	201.8	152.3
	17	8.9	5.6	4.0	3.0	2.0	1.5
85.0	1659	888.8	564.5	400.0	304.6	203.0	153.3
	17	8.9	5.7	4.0	3.1	2.0	1.5
90.0	1656	889.5	565.8	401.4	305.9	204.2	154.3
	17	8.9	5.7	4.0	3.1	2.0	1.5
95.0	1653	890.3	567.1	402.8	307.3	205.4	155.4
	17	8.9	5.7	4.0	3.1	2.1	1.6
100.0	1651	891.1	568.4	404.2	308.6	206.5	156.4
	17	8.9	5.7	4.0	3.1	2.1	1.6

TABLE. 3. Viscosity of water substance—critically evaluated experimental data—Continued

Units: t °C, P MPa, μ 10^{-6}Pa·s

P	250	300	350	375	400	425	450
0.1	18.30	20.36	22.43	23.45	24.47	25.49	26.50
	0.37	0.41	0.45	0.47	0.49	0.51	0.53
0.5	18.16	20.25	22.32	23.43	24.44	25.49	26.53
	0.36	0.41	0.45	0.47	0.49	0.51	0.53
1.0	18.09	20.21	22.29	23.40	24.43	25.49	26.53
	0.36	0.40	0.45	0.47	0.49	0.51	0.53
2.5	17.85	20.07	22.22	23.37	24.41	25.49	26.54
	0.36	0.40	0.44	0.47	0.49	0.51	0.53
5.0	106.5	19.88	22.15	23.33	24.42	25.52	26.60
	1.1	0.40	0.44	0.47	0.49	0.51	0.53
7.5	107.2	19.75	22.12	23.34	24.46	25.58	26.68
	1.1	0.40	0.44	0.47	0.49	0.51	0.53
10.0	107.8	87.1	22.16	23.39	24.52	25.65	26.75
	1.1	1.7	0.44	0.47	0.49	0.51	0.53
12.5	108.5	88.0	22.35	23.57	24.69	25.81	26.91
	1.1	1.8	0.45	0.47	0.49	0.52	0.54
15.0	109.1	89.0	22.84	23.88	24.98	26.06	27.13
	1.1	1.8	0.46	0.48	0.50	0.52	0.54
17.5	109.8	89.9	67.3	24.49	25.37	26.38	27.42
	1.1	1.8	2.0	0.49	0.51	0.53	0.55
20.0	110.4	90.8	69.5	25.85	26.03	26.83	27.80
	1.1	1.8	2.1	0.52	0.52	0.54	0.56
22.5	111.1	91.6	71.4	48.2	27.11	27.50	28.31
	1.1	1.8	2.1	3.9	0.54	0.55	0.57
25.0	111.7	92.4	73.0	58.8	29.10	28.43	28.99
	1.1	1.9	2.2	1.2	0.58	0.57	0.58
27.5	112.3	93.1	74.4	62.4	33.88	29.81	29.84
	1.1	1.9	2.2	1.2	0.68	0.60	0.60
30.0	112.9	93.9	75.7	64.9	43.97	31.84	30.97
	1.1	1.9	2.3	1.3	0.89	0.64	0.62
35.0	114.1	95.3	78.0	68.6	56.4	39.47	34.19
	1.1	1.9	2.3	1.4	1.1	0.79	0.68
40.0	115.3	96.5	79.9	71.3	62.1	49.26	39.16
	1.2	1.9	2.4	1.4	1.2	0.99	0.78
45.0	116.4	97.8	81.7	73.7	65.8	55.6	44.87
	1.2	2.0	2.5	1.5	1.3	1.1	0.90
50.0	117.6	99.0	83.4	75.9	68.2	60.1	50.5
	1.2	2.0	2.5	2.3	2.0	1.8	1.5
55.0	118.7	100.2	84.9	77.8	70.9	63.6	55.3
	1.2	2.0	2.6	2.3	2.1	1.9	1.7
60.0	119.7	101.3	86.3	79.5	73.1	66.1	59.2
	1.2	2.0	2.6	2.4	2.2	2.0	1.8
65.0	120.8	102.5	87.7	81.0	75.2	68.1	62.3
	1.2	2.1	2.6	2.4	2.3	2.0	1.9
70.0	121.9	103.6	89.0	82.5	76.9	70.5	64.9
	1.2	2.1	2.7	2.5	2.3	2.1	2.0
75.0	122.9	104.6	90.3	83.9	78.5	72.2	66.9
	1.2	2.1	2.7	2.5	2.4	2.2	2.0
80.0	123.9	105.6	91.4	85.2	79.9	74.0	68.3
	1.2	2.1	2.7	2.6	2.4	2.2	2.1
85.0	124.9	106.6	92.6	86.4	81.4	75.8	70.2
	1.3	2.1	2.8	2.6	2.4	2.3	2.1
90.0	125.9	107.6	93.7	87.5	82.7	77.2	72.3
	1.3	2.2	2.8	2.6	2.5	2.3	2.2
95.0	126.9	108.6	94.7	88.7	83.6	78.6	73.8
	1.3	2.2	2.8	2.7	2.5	2.4	2.2
100.0	127.9	109.6	95.8	89.8	85.0	79.8	74.6
	1.3	2.2	2.9	2.7	2.6	2.4	2.2

TABLE. 3. Viscosity of water substance—critically evaluated experimental data—Continued

Units: t °C, P MPa, μ 10^{-6} Pa·s

P	475	500	550	600	650	700	750	800
1.0	27.51	28.52	30.53	32.55	34.6	36.6	38.6	40.5
	0.55	0.86	0.92	0.98	1.0	1.1	1.2	1.2
0.5	27.57	28.64	30.67	32.77	34.7	36.7	38.5	40.3
	0.55	0.86	0.92	0.98	1.0	1.1	1.2	1.2
1.0	27.58	28.65	30.68	32.79	34.8	36.8	38.5	40.4
	0.55	0.86	0.92	0.98	1.0	1.1	1.2	1.2
2.5	27.59	28.66	30.72	32.84	34.8	36.8	38.6	40.4
	0.55	0.86	0.92	0.99	1.0	1.1	1.2	1.2
5.0	27.66	28.73	30.82	32.77	34.9	36.9	38.7	40.6
	0.55	0.86	0.92	0.98	1.1	1.1	1.2	1.2
7.5	27.76	28.81	30.94	32.87	34.9	37.0	38.8	40.7
	0.56	0.86	0.93	0.99	1.1	1.1	1.2	1.2
10.0	27.82	28.95	31.08	33.02	35.1	37.2	39.0	40.9
	0.56	0.87	0.93	0.99	1.1	1.1	1.2	1.2
12.5	27.98	29.09	31.19	35.2	35.2	37.4	39.2	41.1
	0.56	0.87	0.94	1.0	1.1	1.1	1.2	1.2
15.0	28.18	29.30	31.44	33.4	35.5	37.6	39.4	41.2
	0.56	0.88	0.94	1.0	1.1	1.1	1.2	1.2
17.5	28.42	29.49	31.70	33.7	35.7	37.8	39.6	41.4
	0.57	0.88	0.95	1.0	1.1	1.1	1.2	1.2
20.0	28.76	29.81	31.98	33.9	35.9	38.0	39.8	41.6
	0.58	0.89	0.96	1.0	1.1	1.1	1.2	1.3
22.5	29.17	30.17	32.38	34.2	36.2	38.2	39.8	41.9
	0.58	0.91	0.97	1.0	1.1	1.2	1.2	1.3
25.0	29.70	30.56	32.73	34.6	36.5	38.5	40.2	41.9
	0.59	0.92	0.98	1.0	1.1	1.2	1.2	1.3
27.5	30.33	31.08	33.11	34.9	36.8	38.7	40.4	42.2
	0.61	0.93	0.99	1.1	1.1	1.2	1.2	1.3
30.0	31.06	31.68	33.6	35.3	37.2	39.0	40.7	42.5
	0.62	0.95	1.0	1.1	1.1	1.2	1.2	1.3
35.0	33.17	33.10	34.6	36.1	37.9	39.8	41.3	43.0
	0.66	0.99	1.0	1.1	1.1	1.2	1.2	1.3
40.0	36.06	35.2	35.7	35.5	38.8	40.4	42.0	43.7
	0.72	1.1	1.1	1.1	1.2	1.2	1.3	1.3
45.0	39.90	37.6	37.4	38.6	40.0	41.2	43.1	44.4
	0.80	1.1	1.1	1.2	1.2	1.2	1.3	1.3
50.0	44.0	40.5	39.1	40.0	40.6	42.2	43.7	45.3
	1.3	1.2	1.2	1.2	1.2	1.3	1.3	1.4
55.0	48.4	43.9	41.0	41.4	41.8	42.5	44.6	45.9
	1.5	1.3	1.2	1.2	1.3	1.3	1.3	1.4
60.0	52.3	47.6	43.1	41.7	42.9	43.2	44.8	46.6
	1.6	1.4	1.3	1.3	1.3	1.3	1.3	1.4
65.0	55.5	50.8	45.1	43.2	43.9	44.2	45.4	46.8
	1.7	1.5	1.4	1.3	1.3	1.3	1.4	1.4
70.0	58.8	53.7	47.5	44.8	44.3	44.4	46.2	47.4
	1.8	1.6	1.4	1.3	1.3	1.3	1.4	1.4
75.0	61.3	56.2	49.7	45.7	45.5	45.6	46.8	48.1
	1.8	1.7	1.5	1.4	1.4	1.4	1.4	1.4
80.0	63.6	58.7	52.1	47.4	47.0	46.6	47.3	48.6
	1.9	1.8	1.6	1.4	1.4	1.4	1.4	1.5
85.0	65.5	60.8	54.0	49.9	47.6	47.6	48.1	49.0
	2.0	1.8	1.6	1.5	1.4	1.4	1.4	1.5
90.0	67.3	62.8	55.8	51.4	48.9	49.1	48.9	49.7
	2.0	1.9	1.7	1.5	1.5	1.5	1.5	1.5
95.0	69.1	64.6	57.7	53.6	50.9	49.5	49.8	50.3
	2.1	1.9	1.7	1.6	1.5	1.5	1.5	1.5
100.0	69.8	66.1	59.3	55.1	52.1	50.5	51.1	51.0
	2.1	2.0	1.8	1.7	1.6	1.5	1.5	1.5

TABLE 4. Viscosity of saturated water and steam—critically evaluated experimental data

t °C	P_s bar	μ' 10^{-6}Pa·s	μ'' 10^{-6}Pa·s
0.00	0.00611	1792.60	8.84
0.01	0.00611	1791.98	8.84
10.00	0.01227	1305.46	9.17
20.00	0.02337	1002.00	9.52
30.00	0.04241	798.44	9.86
40.00	0.07375	653.93	10.18
50.00	0.12335	547.11	10.51
60.00	0.19920	466.01	10.88
70.00	3.31181	403.33	11.28
80.00	0.47360	354.16	11.65
90.00	0.70109	314.76	12.02
100.00	1.01325	281.87	12.37
110.00	1.43266	255.52	12.71
120.00	1.98543	232.95	13.04
130.00	2.70132	213.61	13.37
140.00	3.61379	197.00	13.69
150.00	4.75597	182.69	14.02
160.00	6.18065	170.32	14.35
170.00	7.92023	159.57	14.69
180.00	10.02663	150.17	15.03
190.00	12.55124	141.87	15.38
200.00	15.54880	134.50	15.74
210.00	19.07739	127.88	16.10
220.00	23.19830	121.87	16.46
230.00	27.97605	116.37	16.83
240.00	33.47832	111.27	17.20
250.00	39.77602	106.50	17.57
260.00	46.94337	101.99	17.94
270.00	55.05808	97.69	18.31
280.00	64.20179	93.55	18.69
290.00	74.46073	89.55	19.09
300.00	85.92692	85.64	19.53
310.00	98.70012	81.78	20.03
320.00	112.89087	77.94	20.64
330.00	128.62522	74.00	21.40
340.00	146.05170	69.82	22.39
350.00	165.35124	65.16	23.73
360.00	186.75069	57.72	25.68
370.00	210.54033	52.16	29.72
371.00	213.06432	50.98	30.65
372.00	215.61629	49.66	31.99
373.00	218.19666	48.53	34.22
374.00	220.80523	43.57	38.35
374.15	221.20000	40.60	40.60

taken into account, the tolerances imposed in the critical region were carefully adjusted to encompass its expected value over most of the region, that is with the exception of the rectangle defined by

$$|\rho/\rho_c| - 1 \approx 0.1 \quad \text{and} \quad |T/T_c| - 1 \approx 0.005.$$

3.5. Comparison of the New ICPS Representation with Selected Experimental Data

The new tables and interpolation equations were deduced directly from the experimental data which constitute the International Input, table 2. The deviation plots of figures 12–14 compare the output of the correlating equation with selected experimental data in order to convey to the user the quality of the result.

Figure 12 refers to the liquid phase and shows that the fit to the data of Agayev and Rivkin is very close. In the interval 300–370 °C, the data by Nagashima et al. [53] appear systematically higher than those of Rivkin et al. [54, 55], although no such systematic divergence exists between the same two data sets at lower temperatures.

Comparisons describing the viscosity of steam at atmospheric pressure in the range 100–800 °C are contained in figure 13. The 1964 ST preferred Shifrin's data [65] which were systematically higher than Bonilla's [66]. The figure brings out the fact that this bias was subsequently justified by the newer measurements performed by Latto [67], Sato et al. [68, 69], and Timrot et al. [70]. It seems that more experimental investigations are needed at 100 °C as well as at temperatures above 500 °C.

Figure 14 contains the deviation plot for steam at high pressures.

Figure 15 refers specifically to the 400 °C isotherm and demonstrates the large discrepancies which exist along it between the new base line and 1964 ST. The selected experimental points confirm that the new correlation represents them with an improved accuracy and shows that they depart from the 1964 ST by more than the old tolerances.

The 1964 and the new skeleton tables are seen compared along some typical isotherms in figure 16 which shows deviations of both from eq (6). These reveal the

TABLE 5. Constants in equation (6)

Numerical values of the coefficients b_{ij}

$i =$	0	1	2	3	4	5
$j = 0$	0.501 938	0.162 888	−0.130 356	0.907 919	−0.551 119	0.146 543
1	0.235 622	0.789 393	0.673 665	1.207 552	0.067 0665	−0.084 3370
2	−0.274 637	−0.743 539	−0.959 456	−0.687 343	−0.497 089	0.195 286
3	0.145 831	0.263 129	0.347 247	0.213 486	0.100 754	−0.032 932
4	−0.027 0448	−0.025 3093	−0.026 7758	−0.082 2904	0.060 2253	−0.020 2595

$T^* = 647.27$ K
$\rho^* = 317.763$ kg/m³
$a_0 = 0.018$ 1583
$a_1 = 0.017$ 7624
$a_2 = 0.010$ 5287
$a_3 = −0.003$ 6744

TABLE 6. Viscosity of water substance—calculated with the aid of equation (6)

Units: t °C, P MPa, μ 10^{-6}Pa·s

P	0.0	25.0	50.0	75.0	100.0	150.0	200.0	250.0
0.1	1792	890.8	547.1	378.3	12.28	14.19	16.18	18.22
0.5	1791	890.7	547.2	378.4	282.3	181.9	16.07	18.15
1.0	1790	890.6	547.2	378.6	282.4	182.0	15.93	18.07
2.5	1786	890.2	547.5	378.9	282.8	182.4	133.8	17.83
5.0	1780	889.7	547.9	379.6	283.5	183.1	134.5	106.1
7.5	1775	889.3	548.3	380.2	284.2	183.7	135.1	106.8
10.0	1770	888.9	548.7	380.8	284.8	184.4	135.7	107.5
12.5	1764	888.4	549.1	381.5	285.5	185.0	136.3	108.2
15.0	1759	888.1	549.6	382.1	286.2	185.7	137.0	108.9
17.5	1754	887.7	550.0	382.7	286.9	185.2	137.6	109.5
20.0	1749	887.4	550.5	383.4	287.5	186.9	138.2	110.2
22.5	1744	887.1	550.9	384.0	288.2	187.6	138.8	110.8
25.0	1740	886.8	551.4	384.6	288.9	188.2	139.4	111.4
27.5	1735	886.6	551.8	385.3	289.5	188.8	140.0	112.0
30.0	1731	886.4	552.3	385.9	290.2	189.5	140.5	112.7
35.0	1722	886.0	553.3	387.2	291.6	190.7	141.7	113.8
40.0	1714	885.8	554.3	388.5	292.9	191.9	142.9	115.0
45.0	1707	885.6	555.3	389.8	294.2	193.2	144.0	116.1
50.0	1700	885.5	556.4	391.1	295.6	194.4	145.1	117.3
55.0	1693	885.6	557.5	392.4	296.9	195.6	146.2	118.4
60.0	1687	885.7	558.6	393.7	298.2	196.8	147.3	119.4
65.0	1681	885.9	559.7	395.0	299.6	198.1	148.4	120.5
70.0	1676	886.2	560.9	396.4	300.9	199.3	149.5	121.5
75.0	1671	886.6	562.1	397.7	302.2	200.5	150.6	122.5
80.0	1667	887.1	563.3	399.1	303.6	201.7	151.6	123.6
85.0	1663	887.7	564.6	400.4	304.9	202.9	152.7	124.6
90.0	1659	888.4	565.8	401.8	306.3	204.1	153.7	125.5
95.0	1655	889.1	567.1	403.2	307.6	205.2	154.8	126.5
100.0	1652	890.0	568.5	404.6	309.0	206.4	155.8	127.5

TABLE 6. Viscosity of water substance—calculated with the aid of equation (6)—Continued

Units: t °C, P MPa, μ 10^{-6}Pa·s

P	300.0	350.0	375.0	400.0	425.0	450.0	475.0	500.0
0.1	20.29	22.37	23.41	24.45	25.49	26.52	27.55	28.57
0.5	20.25	22.35	23.39	24.44	25.48	26.52	27.55	28.58
1.0	20.20	22.32	23.37	24.42	25.47	26.51	27.55	28.58
2.5	20.06	22.24	23.32	24.39	25.46	26.52	27.57	28.61
5.0	19.86	22.16	23.27	24.38	25.47	26.55	27.61	28.67
7.5	19.74	22.13	23.28	24.40	25.52	26.61	27.70	28.77
10.0	86.39	22.18	23.35	24.49	25.62	25.72	27.82	28.90
12.5	87.37	22.39	23.52	24.65	25.77	26.88	27.98	29.06
15.0	88.30	22.91	23.84	24.91	26.01	27.10	28.19	29.27
17.5	89.19	66.82	24.45	25.32	26.34	27.39	28.46	29.52
20.0	90.05	69.14	25.77	25.96	26.80	27.77	28.79	29.82
22.5	90.87	71.00	47.44	27.02	27.44	28.26	29.20	30.18
25.0	91.67	72.60	58.18	28.99	28.36	28.89	29.70	30.61
27.5	92.45	74.02	61.91	33.62	29.70	29.71	30.31	31.11
30.0	93.20	75.30	64.49	43.67	31.74	30.78	31.06	31.70
35.0	94.64	77.59	68.24	55.74	39.26	33.99	33.07	33.19
40.0	96.01	79.60	71.10	61.26	48.62	39.03	35.93	35.17
45.0	97.32	81.43	73.48	64.95	55.01	45.18	39.71	37.69
50.0	98.58	83.10	75.56	67.81	59.38	50.69	44.08	40.70
55.0	99.81	84.67	77.44	70.20	62.70	55.03	48.37	44.03
60.0	101.0	86.14	79.16	72.28	65.39	58.48	52.17	47.40
65.0	102.1	87.53	80.75	74.15	67.69	61.32	55.40	50.56
70.0	103.2	88.86	82.25	75.87	69.70	63.74	58.17	53.41
75.0	104.3	90.13	83.66	77.45	71.52	65.86	60.57	55.95
80.0	105.4	91.36	85.00	78.94	73.18	67.75	62.69	58.21
85.0	106.4	92.54	86.28	80.35	74.73	69.46	64.59	60.24
90.0	107.4	93.69	87.52	81.68	76.18	71.04	66.32	62.08
95.0	108.4	94.80	88.70	82.96	77.55	72.51	67.90	63.76
100.0	109.4	95.89	89.85	84.18	78.85	73.90	69.37	65.31

TABLE 6. Viscosity of water substance—calculated with the aid of equation (6)—Continued

Units: t °C, P MPa, μ 10^{-6}Pa·s

P	550.0	600.0	650.0	700.0	750.0	800.0
0.1	30.61	32.61	34.60	36.55	38.48	40.37
0.5	30.61	32.63	34.61	36.57	38.50	40.39
1.0	30.63	32.64	34.63	36.59	39.52	40.42
2.5	30.67	32.70	34.70	36.66	38.59	40.50
5.0	30.76	32.81	34.82	36.79	38.73	40.63
7.5	30.87	32.93	34.95	36.93	38.88	40.78
10.0	31.01	33.09	35.11	37.09	39.04	40.94
12.5	31.18	33.26	35.29	37.27	39.21	41.11
15.0	31.38	33.46	35.48	37.46	39.39	41.29
17.5	31.62	33.68	35.69	37.66	39.59	41.48
20.0	31.89	33.92	35.93	37.89	39.80	41.68
22.5	32.19	34.20	36.18	38.12	40.03	41.89
25.0	32.54	34.50	36.45	38.38	40.27	42.12
27.5	32.93	34.83	36.75	38.65	40.51	42.35
30.0	33.37	35.20	37.07	38.93	40.78	42.59
35.0	34.39	36.02	37.77	39.55	41.34	43.10
40.0	35.65	36.97	38.55	40.23	41.94	43.65
45.0	37.14	38.06	39.43	40.98	42.60	44.24
50.0	38.88	39.29	40.39	41.78	43.29	44.85
55.0	40.84	40.64	41.44	42.64	44.03	45.50
60.0	42.96	42.11	42.55	43.55	44.79	46.17
65.0	45.19	43.66	43.73	44.50	45.59	46.86
70.0	47.45	45.28	44.96	45.48	46.41	47.56
75.0	49.65	46.93	46.22	46.49	47.26	48.28
80.0	51.75	48.58	47.50	47.52	48.11	49.01
85.0	53.72	50.20	48.79	48.55	48.97	49.74
90.0	55.54	51.77	50.06	49.59	49.83	50.48
95.0	57.25	53.28	51.31	50.62	50.69	51.20
100.0	58.84	54.71	52.52	51.62	51.53	51.93

TABLE 7. Viscosity of saturated water and steam calculated with the aid of equation (6)

t °C	μ' 10^{-6}Pa·s	μ'' 10^{-6}Pa·s	t °C	μ' 10^{-6}Pa·s	μ'' 10^{-6}Pa·s
0.00	1791.9	9.22	220.00	121.0	16.49
0.01	1791.3	9.22	230.00	115.5	16.85
10.00	1307.6	9.46	240.00	110.5	17.22
20.00	1002.6	9.73	250.00	105.8	17.59
30.00	797.7	10.01	260.00	101.5	17.98
40.00	653.1	10.31	270.00	97.36	18.38
50.00	547.1	10.62	280.00	93.41	18.80
60.00	466.8	10.94	290.00	89.58	19.25
70.00	404.4	11.26	300.00	85.81	19.74
80.00	354.9	11.60	310.00	82.06	20.28
90.00	315.0	11.93	320.00	78.27	20.89
100.00	282.2	12.28	330.00	74.37	21.62
110.00	254.9	12.62	340.00	70.21	22.52
120.00	232.1	12.92	350.00	65.68	23.72
130.00	212.7	13.32	355.00	63.12	24.51
140.00	196.1	13.67	360.00	60.21	25.53
150.00	181.9	14.02	365.00	56.61	26.97
160.00	169.6	14.37	370.00	51.43	29.35
170.00	158.8	14.72	371.00	50.07	30.11
180.00	149.4	15.07	372.00	48.30	31.08
190.00	141.0	15.42	373.00	46.07	32.51
200.00	133.6	15.78	374.12	38.61	38.61
210.00	127.0	16.13			

existence of considerable differences in the steam region between 375 °C and 500 °C, which means that the tolerances of 1964 were too optimistic. It is clear that the differences between the old and new formulations are due to the fact that they both have been calculated on different primary data bases as explained earlier in sections 2.6 and 3.2.

3.6. Effect of Different Sources for Values of Density

When the density is calculated with the aid of 1967 IFC Formulation widely used throughout the world's industry, eq (6) will yield a viscosity value which is generally lower than that resulting from the use of the 1968 IFC Formulation. For example, at 350 °C and 100 MPa this is lower by 0.4%, and at 375 °C and 22.5 MPa the difference attains 2.2%. Typical comparisons are given in Appendix VI. The effect of these two alternative sources for data on density at 375 °C is described graphically in figure 17. This effect can be roughly summarized by noting that

$$\Delta\mu/\mu \approx 3\Delta\rho/\rho \quad \text{along the 100 °C isotherm (water phase)}$$

$$\approx 1.5\Delta\rho/\rho \quad \text{along the 300 °C isotherm (water phase)}$$

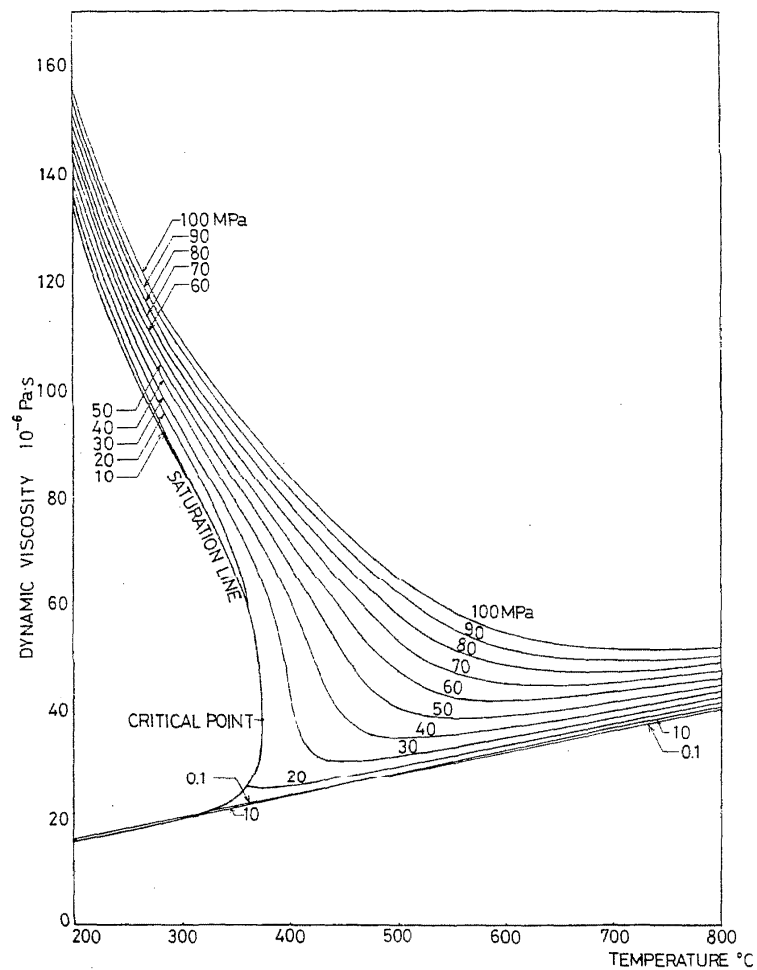$$< 0.5\Delta\rho/\rho \quad \text{for } \rho < \rho_c$$

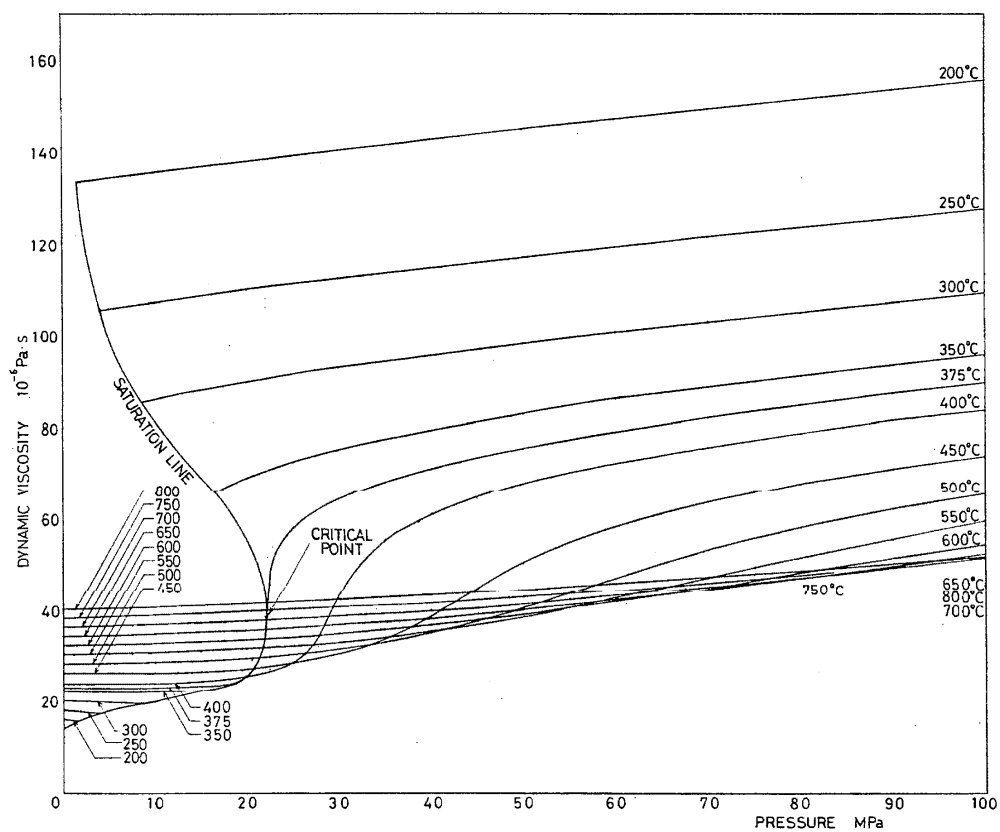FIGURE 8. Dynamic viscosity along isobars

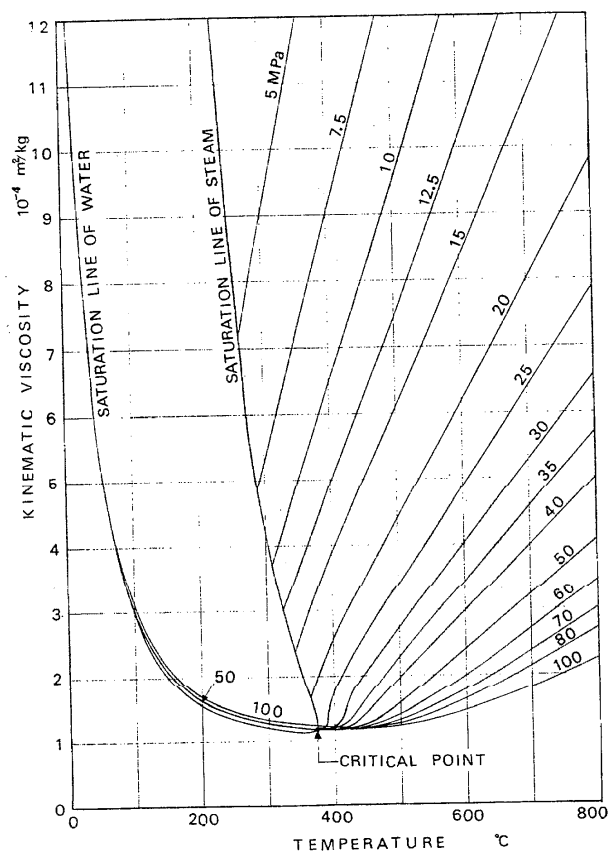FIGURE 9. Dynamic viscosity along isotherms

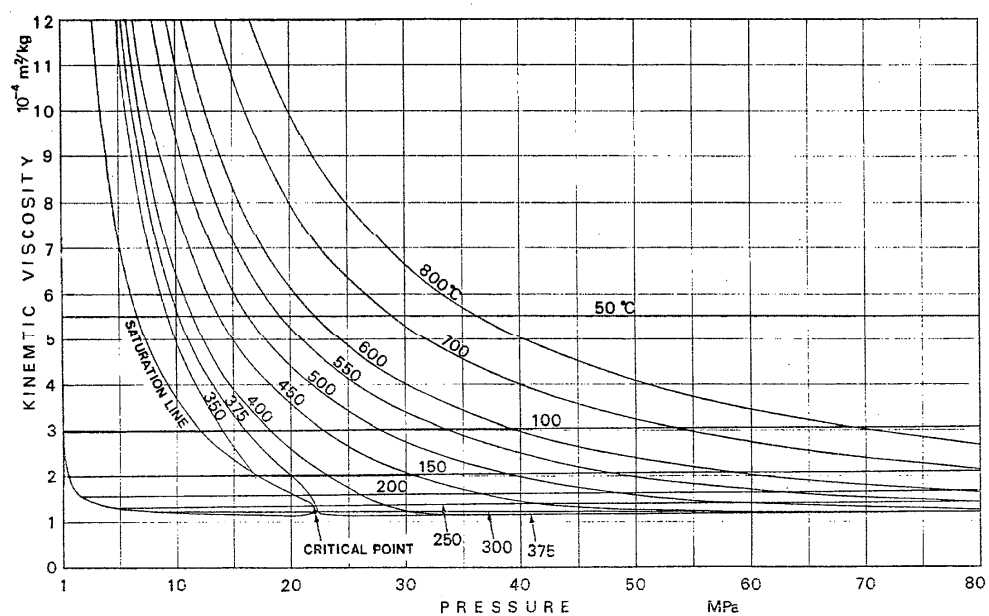FIGURE 10. Kinematic viscosity along isobars

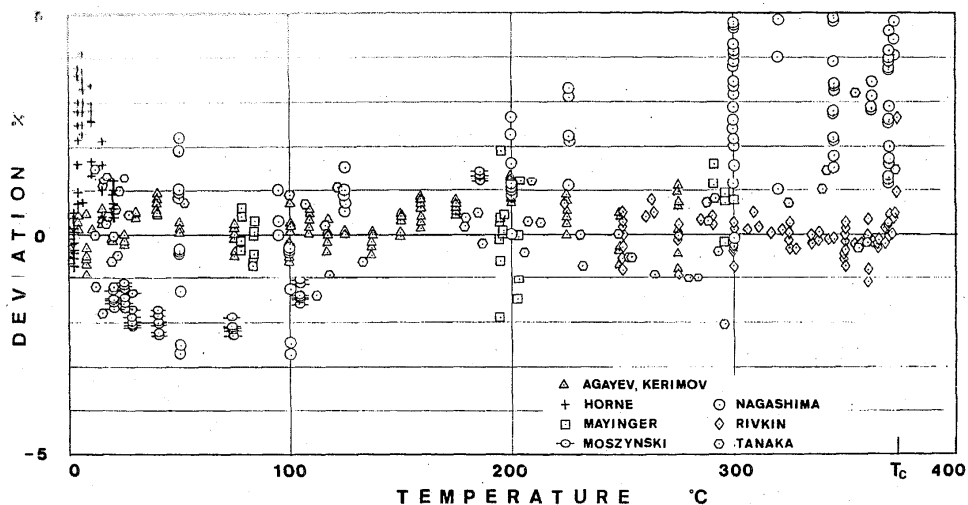FIGURE 11. Kinematic viscosity along isotherms

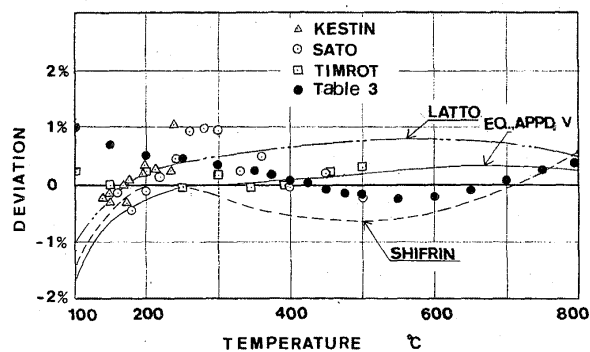FIGURE 12. Deviation of experimental data from equation (6)—water

FIGURE 13. Deviation of experimental data from equation (6)—
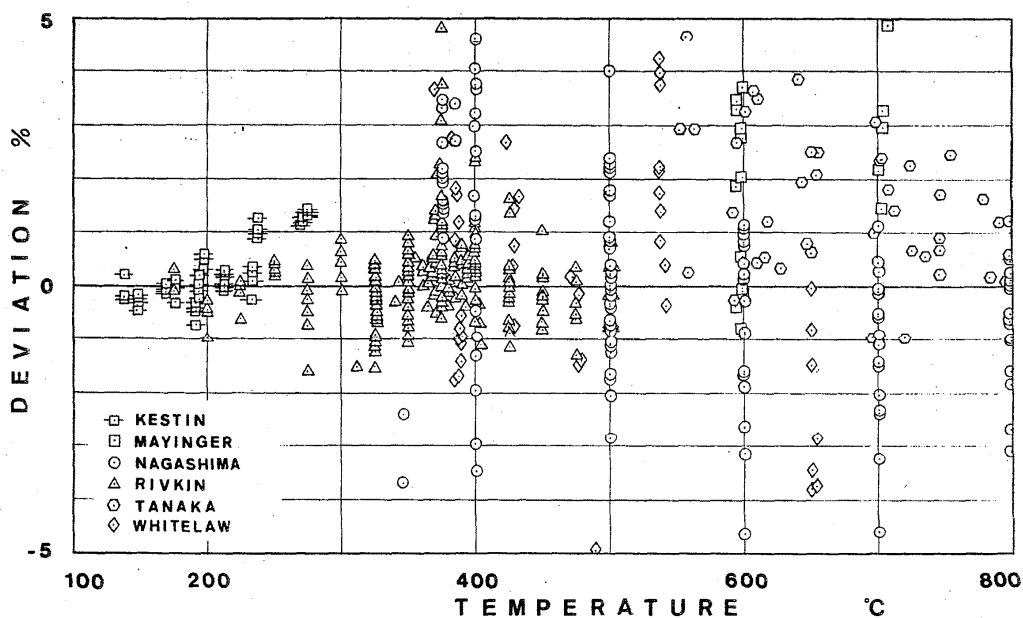steam at atmospheric pressure

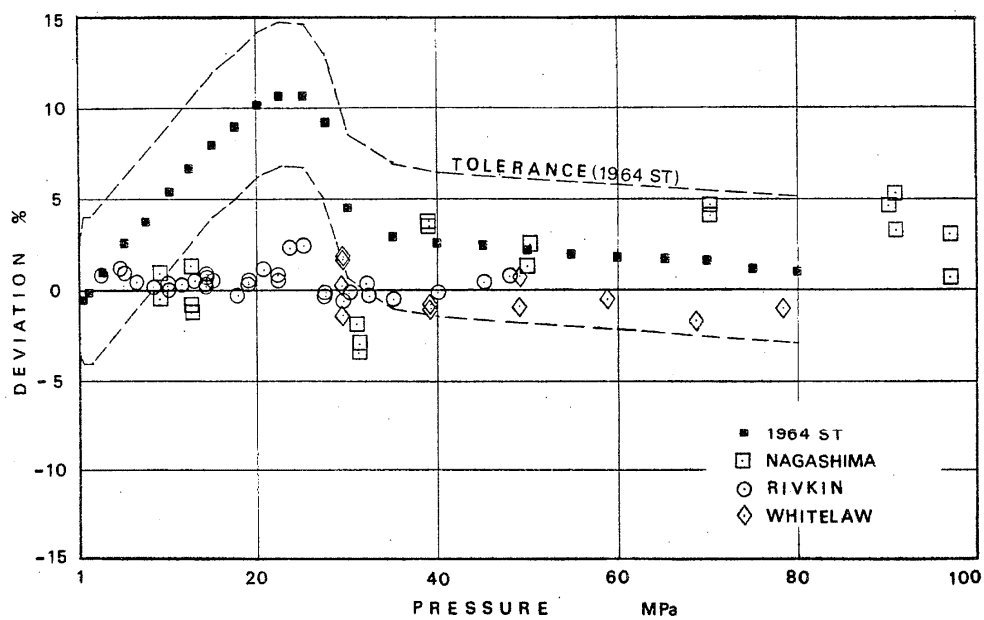FIGURE 14. Deviation of experimental data from equation (6)—steam
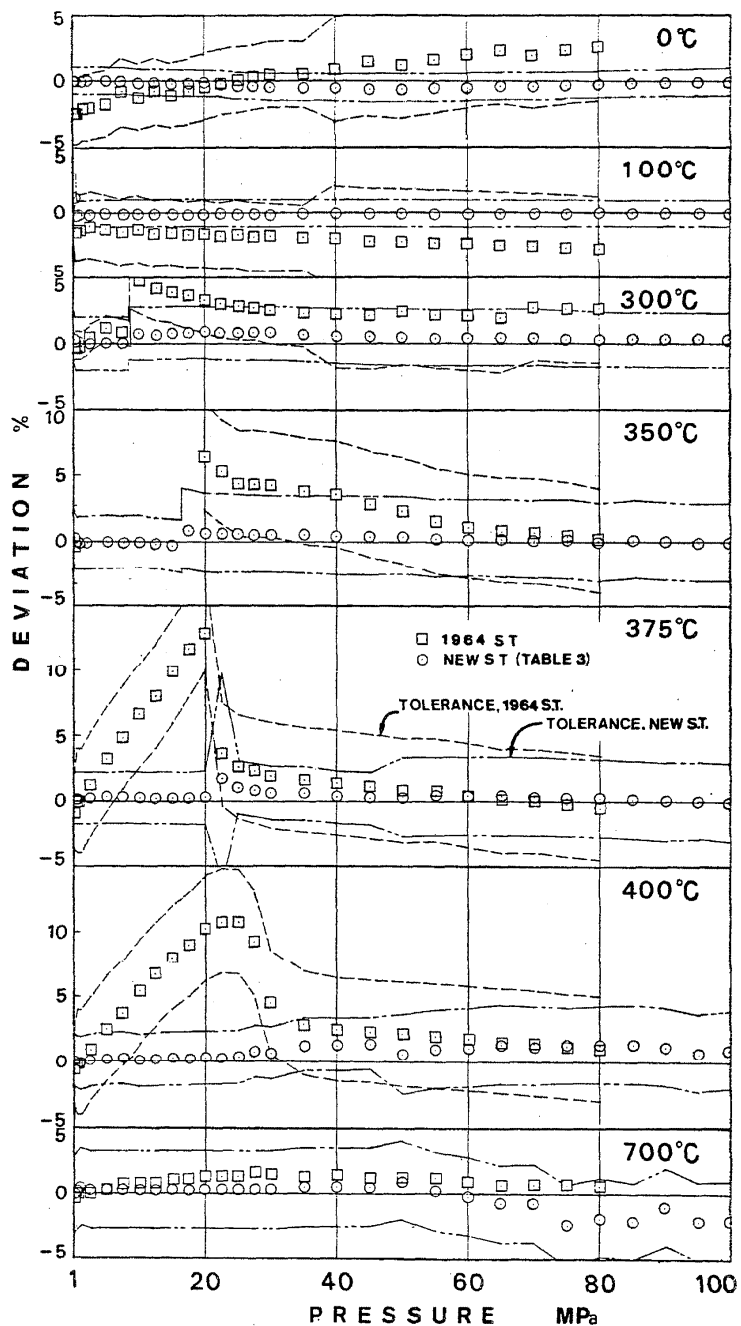
FIGURE 15. Deviations from equation (6)—400 °C

FIGURE 16. Comparison of the former and the new skeleton tables from equation (6)
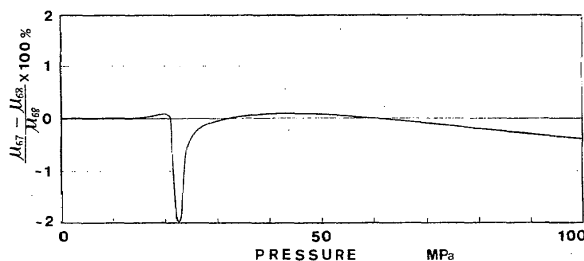
FIGURE 17. Effect of different density sources on the viscosity cal-
culated with equation (6)

μ_{67}: viscosity with eq (6) and the 1967 IFC Formula-
tion

μ_{68}: Viscosity with eq (6) and the 1968 IFC Formula-
tion

4. Concluding Remarks

Our collective knowledge of the viscosity of water and
steam has now progressed significantly forward and has
been crystallized into the new IAPS representation as a
result of the considerable effort mounted during the last
decade.

One of the most interesting topics left for future study
is the behavior of viscosity in the critical region. Neither
the actual magnitude nor the functional form of this
anomaly are now known satisfactorily. Similarly, a theo-
retical study of the viscosity of both the liquid and the
gas is still being awaited.

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6. References

[1] Official Report of Thermal Conductivity Panel of Sixth
International Conference on the Properties of Steam
(1964).

[2] Kestin J., and Whitelaw, J. H., Trans. ASME 8A, 82(1966).

[3] Minutes of Ordinary General Meeting of the IAPS, Giens
(1974).

[4] Theon-Hellemans, J., and Mason, E. A., Int. J. Eng. Sci. 11,
1247(1973).

[5] Swindells, J. F., Coe, J. R., and Godfrey, T. B., J. Res. NBS
48, 1 1(1952).

[6] Cited in Bingham, E. C., Fluidity and Plasticity (1922), also
in ref. 16.

[7] Graham, Phil. Trans. 151, 373(1861).

[8] DeHaas, M., Commun. Phys. Lab. Univ. Leiden 12, 1(1894).

[9] Sprung, A., Pogg. Ann. 159, 1(1876).

[10] Grotrian, O., Pogg. Ann. 160, 238(1877).

[11] Slotte, K. F., Wied. Ann. 20, 257(1883).

[12] Noak, K., Wied. Ann. 27, 289(1886).

[13] Thorpe, T. E., and Rodger, J. W., Phil. Trans. 185A, 397
(1894).

[14] Heydeweiller, A., Wied. Ann. 59, 193(1896).

[15] Hosking, R., Phil. Mag. VI 18, 260(1909).

[16] Bingham, E. C., and White, G. E., Z. Phys. Chem. 80, 670
(1912).

[17] Bingham, E. C., and Jackson, R. F., Bull. NBS 14, 59(1919).

[18] White, G. F., and Twining, R. H., J. Amer. Chem. Soc. 50,
380(1914).

[19] Leroux, P., Compt. Rend. 180, 914(1925), Ann. de Phys.
10–4, 163(1926).

[20] Geddes, J. A., J. Amer. Chem. Soc. 55, 4832(1933).

[21] Wobser, R., and Mueller, F., Kollard-Beihefte 52, 165(1941).

[22] Coe, J. R. Jr., and Godfrey, T. B., J. Appl. Phys. 15, 625
(1944).

[23] Hardy, R. C., and Cottington, R. L., J. Res. NBS 42, 573
(1949).

[24] Hoeppler, F., Z. angew., Phys. IV 8, 297(1952).

[25] Jaumotte, A., Rev. Universelle mine 17, 213(1951).

[26] Weber, W., Z. angew L., Phys. 7, 96(1955).

[27] Roscoe, R., and Bainbridge, W., Proc. Phys. Soc. 72, 585
(1958).

[28] Caw, W. A., and Wylie, R. G., Nature 189, 995(1961).

[29] Hallet, J., Proc. Phys. Soc. 82, 1046(1963).

[30] Korosi, A., and Fabuss, B. M., Anal. Chem. 40, 157(1968).

[31] Korson, L., Drost-Hansen, W., and Millero, F. J., J. Phys.
Chem. 73, 34(1969).

[32] Penn, R. W., and Kearsley, E. A., J. Res. NBS **75A**, 553 (1971).

[33] Marvin, R. S., J. Res. NBS **75A**, 535(1971).

[34] Malyarov, G. A., Trudi VNIIM, 37/97(1959).

[35] Eicher, L. D., and Zwolinski, B. J., J. Phys. Chem. **75**, 2016 (1971).

[36] Kawata, M., et al., Proc. 5th Int. Congr. Rheology **1**, 453 (1969).

[37] Kestin, J., and Whitelaw, J. H., Phys. Fluids **9**, 1032(1966).

[38] White, H. S., and Kearsley, E. A., J. Res. NBS **75A**, 541 (1971).

[39] Grigull, U., Proc. 8th ICPS, Giens, Vol. 1, 113(1974).

[40] For example, Kawata et al., Paper 6th Int. Congr. Rheology, France (1972).

[41] Kestin, J., et al., Appl. Sci. Res. **27**, 241(1973).

[42] Ikeda, M., and Nagashima, A. (to be published).

[43] Maylinger, F., Int. J. Heat Mass Transfer **5**, 807(1962).

[44] Timrot, D. L., and Khlopkina, A. V., Teploenergetika **10**-7, 64(1963).

[45] Moszynski J. R., Trans. ASME **83**, 111(1961).

[46] Dudziak, K. H., and Franck, E. U., Ber. Bunsen, **70**, 1120 (1966).

[47] Bett, K. E., and Cappi, J. B., Nature **207**, 620(1965); also in Bruggs, E. A., et al., 7th ICPS, Tokyo, Paper B–160(1968).

[48] Horne, R. A., and Johnson, D. S., J. Phys. Chem. **70**, 2182 (1966).

[49] Agayev, N. A., and Usibova, A. D., Dokladi AN SSSR **180**, 334(1968).

[50] Agayev, N. A., and Usibova, A. D., Teploenergetika **14**, 75 (1967-9).

[51] Kerimov, A. M., Agayev, N. A., and Abaszade, A. A., Teplo-energetika **18**–11, 87(1969).

[52] Tanaka, K., et al., Trans. JSME **31**, 1847(1965).

[53] Nagashima, A., and Tanishita, I., Bull. JSME **12**, 1467 (1969); also, Nagashima, A., et al., 7th ICPS, Tokyo, Paper B–4 (1968).

[54] Rivkin, S. L., Levin, A. Ya., and Izrailevskii, L. B., Teplo-energetika **17**–79(1970).

[55] Rivkin, S. L., et al., Teplo i Massoperenos **7**, 61(1972).

[56] Roentgen, W. C., Ann. Physik **22**, 510(1884).

[57] Warburg, E., and Sachs, J., Ann. Physik **22**, 518(1884).

[58] Cohen, R., Ann. Physik **45**, 666(1892).

[59] Hauser, L., Ann. Physik **5**, 597(1901).

[60] Bridgman, P. W., Proc. Acad. Arts. Sci. **61**, 57(1926).

[61] Sigwart, K., Forsch. Ing.-Wes. **7**, 125(1936).

[62] Golubev, I. F., Trudi GAIP **1**, 7(1953): also. Golubev. I. F., Vyaskosti Gazov i Gazovykh Smesei, Moscow, (1959).

[63] Weber, W., Z. ang. Phys. **7**, 96(1955).

[64] Wonham, J.,   Proc. Thermod. Fluid. Mech. Conv., Liver-pool, 180-3J. (1966).

[65] Shifrin, A. S., Teploenergetika **6**–9, 22(1959).

[66] Bonilla, C. F., Wang, S. J., and Weiner, H., Trans. ASME **78**, 1285(1956).

[67] Latto, B., Int. J. Heat Mass Transfer **8**, 689(1965).

[68] Sato, T., Minamiyama, T., Yata, J., and Oka, T., 7th ICPS Paper B–5, Tokyo, (1968).

[69] Sato, T., et al., Paper of Annual Meeting, Kansai Div. of JSME, (1970).

[70] Timrot, D. L., et al., Teploenergtika **20**–8, 78(1973).

[71] Kundt, A., and Warburg, E., Pogg. Ann. **155**, 337 and 525 (1875).

[72] Puluj, J., Sitz-Berichte Österr. Akad. Wiss., Wien **II–78**, 279 (1878).

[73] Vogel, H., Ann. Physik **43**, 1235(1914).

[74] Smith, C. J., Proc. Roy. Soc. London **A106**, 83(1924).

[75] Braune, H., and Linke R., Z. phys. Chemie **A148**, 195(1930).

[76] Zhidanob, A. G., et al., Inzh. Fiz. Zhur. **15**, 1120(1968).

[77] Krieger, F. J., Proj. R. A. N. D. Report, No. 646(1951).

[78] Kestin, J., and Wang, H. E., Physica **26**, 575(1960).

[79] Moszynski, J. R., PhD Thesis, Univ. London (1958).

[80] Kestin, J., and Richardson, P. D., Trans. ASME **85**, 295 (1963).

[81] Rivkin, S. L., and Levin, A. Ya., Teploenergetika **13**-4, 79 (1966).

[82] Rivkin, S. L., Levin, A. Ya., and Izrailevskii, L. B., Teploener-getika **15**–12, 74(1968).

[83] Speyerer, H., Z. VDI **69**, 747(1925).

[84] Shukayev, W., Zhur. Eksp. Tekhn. Fiz. **3**, 3(1933).

[85] Schiller, W., Forsch. Ing.-Wes. **5A**, 71(1934).

[86] Sigwart, K., Forsch. Ing.-Wes. **7**, 125(1936).

[87] Hawkins, G. A., et al., Trans. ASME **57**, 395(1935).

[88] Shugayev, W., and Sorokin, S., Zhur. Fiz. **9**, 930(1939).

[89] Hawkins, G. A., et al., Trans. ASME **62**, 677(1940).

[90] Jackson, T. W., Thesis, Purdue Univ. (1949).

[91] Jackson, T. W., and Thomas, F. A., Thermod. Transport Prop. Gases, Liq. Solids, McGraw-Hill, 339(1959).

[92] Osborne, H. H., Thesis-Purdue Univ. (1958), also, Disserta-tion Abstr. **19**, 2047(1959).

[93] Witzell, O. W., ASME Paper 61–WA–331 (1961).

[94] Barua, A., and Gupta, A., Trans. Faraday **59**, 2243(1963).

[95] Abe, S., and Nagashima, A., to be published.

[96] Nagashima, A., Tanishita, I., and Murai, Y., J. Chem. Eng. Data **19**, 212(1974).

[97] Timrot, D. L., J. Res. USSR **2**, 419(1940).

[98] Whitelaw, J. H., J. Mech. Eng. Sci. **2**, 288(1960).

[99] Barnett, S. C., Jackson, T. W., and Whiteside, R. H., ASME Paper No. 63–WA–240 (1963).

[100] Jackson, T. W., et al., Adv. Thermophys. Prop. at Extreme Temp. Pres., ASME (1965).

[101] Ray, A. K., J. Mech. Eng. Sci. **6**, 137(1964).

[102] Rivkin, S. L., Levin., A. Ya, and Izrailevskii, L. B., Izv. AN BSSR, Minsk **1**, 33(1972).

[103] Rivkin, S. L., et al., Teploenergetika **20**-8, 11(1973).

[104] Rivkin, S. L., Levin, A. Ya., and Izrailevskii, L. B., Teploener-getika **17**-8, 88(1970).

[105] Nagashima, A., Invited paper, Proc. 8th ICPS, Giens, 81 (1974).

[106] Mayinger, F., et al., Proc. 8th ICPS, Giens, 145(1974).

[107] Sengers, J. V., AIP Conf. Proc. No. 11, Amer. Inst. Phys. 229(1973).

[108] Kestin, J., Whitelaw, J. H., and Zien, T. F., Physica **30**, 161(1964).

[109] Naldrett, S. N., and Maass, O., Can. J. Res. **B18**, 322 (1940).

[110] Iwasaki, H., and Takahashi, M., Proc. 4th Int. High Pres. Conf., Kyoto, 523(1974).

[111] Strumpf, H. I., Collings, A. F., and Pings, C. J., J. Chem. Phys. **60**, 3109(1974).

[112] Rivkin, S. L., et al., Proc. 8th ICPS, Giens, 153(1974).

[113] Schmidt, E. (ed.), Properties of Water and Steam in SI-Units, Springer (1969).

[114] The 1966 IFC Formulations for Scientific and General Use, IFC of 6th ICPS (1968).

[115] Bruges, E. A., et al., Int. J. Heat Mass Transfer **9**, 465 (1966).

[116] Sato, T., and Minamiyama, T., Inst. J. Heat Mass Transfer **7**, 199(1964).

[117] Rivkin, S. L., Paper to IFC, ICPS (1966).
[118] Miyabe, K., and Nishikawa, K., Memoir Fac. Eng., Kyushu Univ. **27**-4, 221 (1967).
[119] Bruges, E. A., and Gibson, M. R., Glasgow Univ. Tech. Rep., No. 25, (1968).
[120] Grigull, U., Mayinger, F., and Bach, J., Wärme-u. Stoffuebertragung **1**, 15 (1968).
[121] Tanishita, I., Watanabe, K., and Oguchi, K., 7th ICPS Paper, Tokyo, No. B-7, (1968).
[122] Stein, W. A., Wärme-u. Stoffuebertragung **2**, 210 (1969).
[123] Tanishita, I., Nagashima, A., and Murai, Y., Bull. JSME **14**, 1178 (1971).
[124] Kesselman, P. M., et al., Teploenergetika **17**-12, 58 (1970).
[125] Kesselman, P. M., et al., Teploenergetika **20**-6, 74 (1973).
[126] Lukas, K., Wärme-u. Stoffuebertragung **4**, 236 (1971).
[127] Mamedov, A. M., et al., Teploenergetika **20**-6, 72 (1973).
[128] Rivkin, S. L., et al., Teploenergetika **20**-1, 68 (1973).
[129] Nagashima, A., et al., Proc. 8th ICPS, Giens, 131 (1974).
[130] Aleksandrov, A. A., Ivanov, A. J., and Matveev, A. B., Draft of the Skeleton Tables for Dynamic Viscosity of Water and Steam, Part I and II (1974).
[131] Nagashima, A., Ikeda, M., Available Input of the Viscosity of Water and Steam (1973).
[132] Scheffler, K., Rosner, N., and Reimann, M., Available Input of the Dynamic Viscosity of Water Substance, TU Munchen (1973).
[133] Nagashima, A., On the International Input (1973).
[134] Rosner, N., et al., Draft of the Skeleton Table for Dynamic Viscosity of Water and Steam, TU Munchen (1975).
[135] Kjelland-Fosterud, E., J. Mech. Eng. Sci., **1**, 30 (1959).
[136] Bonilla, C. F., et al., ASME Int. Mech. Eng. Heat Transfer Symp. Sec. II, 167 (1951).
[137] Mayinger, F., and Oltermann, H., to be published.

Appendix I

The Eighth International Conference on the Properties of Steam, Giens, France, September 1974

Release on Dynamic Viscosity of Water Substance

September 1975
Unrestricted publication allowed in all countries.
Issued by the International Association for the Properties of Steam.
President:
Professor Joseph Kestin, Brown University,
Providence, Rhode Island 02912, USA
Executive Secretary:
Dr. Howard J. White, Jr., Office of Standard Reference Data, National Bureau of Standards, Washington, D.C. 20234, USA

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

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

The Special Committee met in Schliersee near Munich in April 1975 and in Ottawa in September 1975, and completed its work with respect to the representation of the dynamic viscosity of water substance.

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

This Release on Dynamic Viscosity is now issued by the Secretariat under the full authority of the Eighth Conference, and presents in the accompanying Appendices the *International Representation of the Dynamic Viscosity of Water Substance, 1975*.

Work on thermal conductivity is still in progress and a *Supplementary Release on the Thermal Conductivity of Water Substance* will appear at a future date.

A full report of the meeting of the Working Group in Schliersee near Munich, Federal Republic of Germany, and in Ottawa, Canada is contained in the *Official Reports of the Secretary* which can be obtained by writing to

Dr. Howard J. White, Jr.
Office of Standard Reference Data
National Bureau of Standards
Washington, D.C. 20234 USA

Attachments:

Appendices A, B, C, D, and E

Appendix A

The Special Committee considers that the existing data in the literature, which have been collected in the document, "International Input of the Dynamic Viscosity of Water Substance", K. Scheffler, N. Rosner, and M. Reimann, Institute A fuer Thermodynamik, Technische Universitaet Muenchen, September 1973, revised December 1974, are not sufficiently accurate and precise to allow definition of a two-dimensional representation that satisfies all of the criteria for smoothness and physical plausibility that can logically be required of it. The Special Committee draws attention to this fact and hopes that additional measurements of superior quality will become available in the future. At the present time, the Special Committee issues a formulation consisting of a table and an equation.
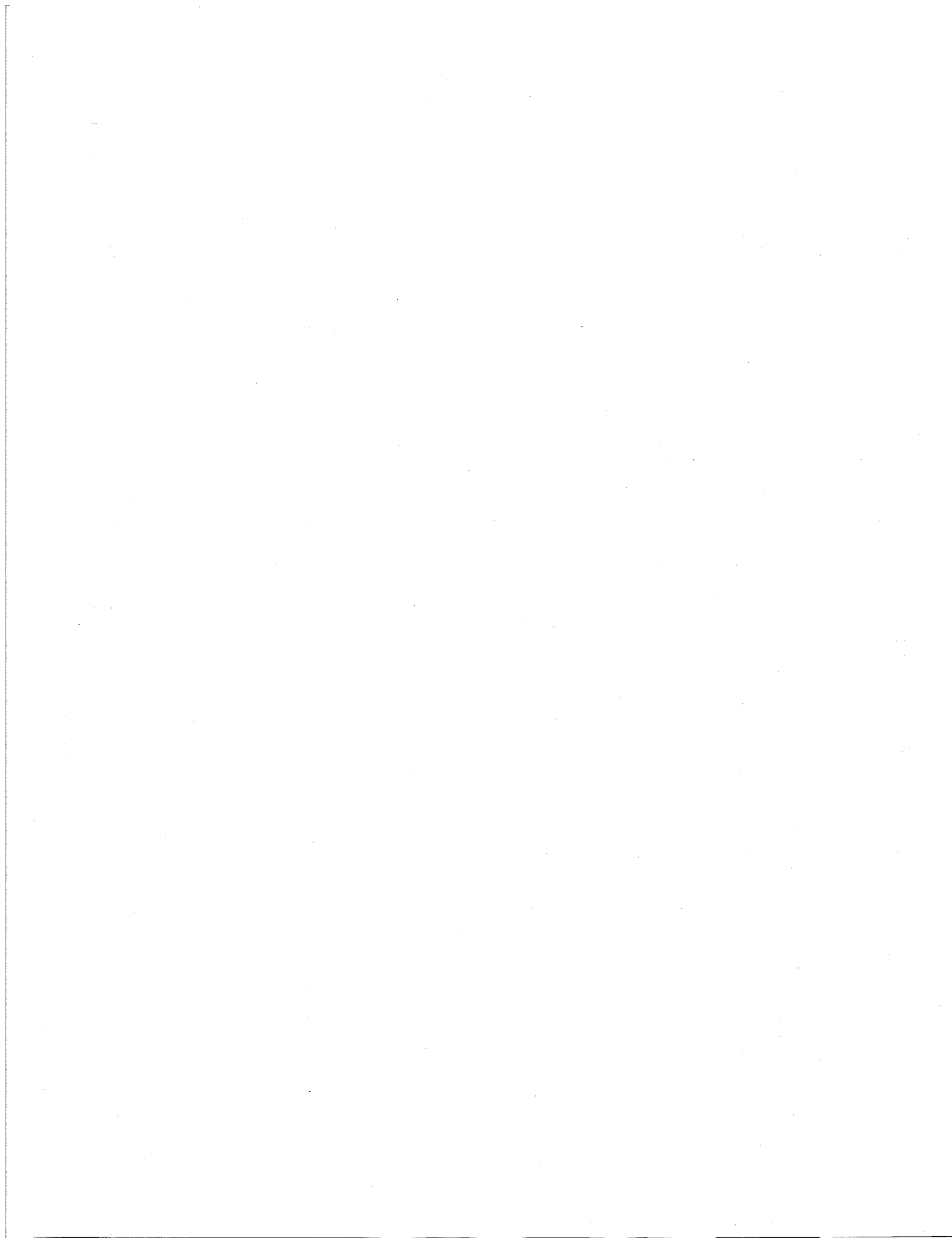
Part 1, Appendix B, contains a Table of *Critically Evaluated Experimental Data* which have been reduced to a uniform grid. The Table and the algorithm used for the reduction are given in the paper, "Draft of the Skeleton Table for Dynamic Viscosity of Water and Steam", by N. Rosner, M. Riemann, K. Scheffler, and U. Grigull, Institute A fuer Thermodynamik, Technische Universitaet Muenchen, January 1975.

The table gives tolerances which constitute estimates of the reliability of the values given and which have been agreed upon by the Special Committee.

Part 2, Appendix C, contains a *Recommended Interpolation Equation*. This equation fits the data given in Table 1 within the tolerances assigned and is considered to be as good a formulation of these data as is available at the present time. A discussion of the equation and its derivation is given in the Draft of the Skeleton Tables for Dynamic Viscosity of Water and Steam, by A. A. Aleksandrov, A. J. Ivanov, and A. B. Mateev, presented to the meeting of Working Group II on transport properties of the IAPS, Moscow, USSR, May 1974; and Draft of the Skeleton Tables of the Dynamic Viscosity of Water and Steam, Part II, by A. A. Aleksandrov, A. H. Ivanov, and A. B. Mateev, presented to the meeting of Working Group II on transport properties of the IAPS, Giens, France, September 1974.

Part 3, Appendix D, gives a table of values at the selected grid points obtained from the equation given in Part 2. These represent smoothed and internally consistent values of the experimental data and are included for practical convenience.

The Special Committee recognizes that:

(a) Table 1 represents an objective rendering of existing experimental data even though its values do not correspond to the Special Committee's conception of "smoothness",

(b) the Interpolation Equation as well as Table 2 do not adequately represent the anomaly which is associated with the dynamic viscosity of pure substances in the critical region (see the paper, "Transport Properties of Gases and Binary Liquid near the Critical State", by J. V. Sengers in "Transport Phenomena—1973", J. Kestin, ed. AIP Conference Proceedings No. 11, American Institute of Physics, New York, 1973, p. 229).

The Special Committee is of the opinion that the corrections needed to represent this anomaly are of the same order of magnitude as the tolerances in that region, except for a rectangle defined by $|\rho/\rho_c - 1| \approx 0.1$ and $|T/T_c - 1| \approx 0.005$, and may be disregarded at the present time.

Appendix B

Part 1. Table of Critically Evaluated Experimental Data (Reduced to a Uniform Grid)

Upper value: viscosity of water or steam, μ in μPa s ($\equiv 10^{-6}$ kg/m · s)

Lower value: uncertainty in the viscosity, $\pm \Delta \mu$ in μPa s ($\equiv 10^{-6}$ kg/m · s)

Pressure P in MPa; Temperature t in °C.

Appendix B, Part 1.

Dynamic Viscosity of Water and Steam

(Same as table 3 in text)

Appendix C

Part 2. Recommended Interpolating Equation

The values appearing in table 1 (same as table 6 in text) may be reproduced within the stated tolerances by the use of the formula given below, wherein

μ denotes the dynamic viscosity

ρ denotes density †

T denotes absolute temperature on the 1968 Practical Temperature Scale

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

a_k and b_{ij} are numerical constants.

$$\mu = \mu_0 \exp\left[\frac{\rho^*}{\rho} \sum_{i=j}^{5} \sum_{j=0}^{4} b_{ij} \left(\frac{T^*}{T} - 1\right)^i \left(\frac{\rho}{\rho^*} - 1\right)^j\right], \quad (1)$$

where

$$\frac{\mu_0}{\mu\text{Pa} \cdot \text{s}} = \left(\frac{T}{T^*}\right)^{1/2} \left[\sum_{k=0}^{3} a_k \left(\frac{T^*}{T}\right)^k\right]^{-1}. \quad (2)$$

The constants appearing in the preceding equations have the numerical values given below and in table a for b_{ij}:

$$\left.\begin{array}{l} T^* = 647.27 \text{ K} \\ \rho^* = 317.763 \text{ kg/m}^3 \end{array}\right\} \quad (3)$$

$$\left.\begin{array}{l} a_0 = \quad 0.018\ 1583 \\ a_1 = \quad 0.017\ 7634 \\ a_2 = \quad 0.010\ 5287 \\ a_3 = -0.003\ 6744 \end{array}\right\} \quad (4)$$

The correlating equation presented in this Appendix is valid in the range

$$0 < t < 800 \text{ °C}$$

in temperature, and

$$0 < \rho < 1050 \text{ kg/m}^3$$

---

† For preference and to reproduce the values given in Appendix D, the density should be computed with the aid of the 1968 IFC Formulation for Scientific and General Use. If another density formulation is used, a relative departure of $\Delta\rho/\rho$ induces at most a relative departure $\pm \Delta\mu/\mu = 2.5 \Delta\rho/\rho$ in viscosity.
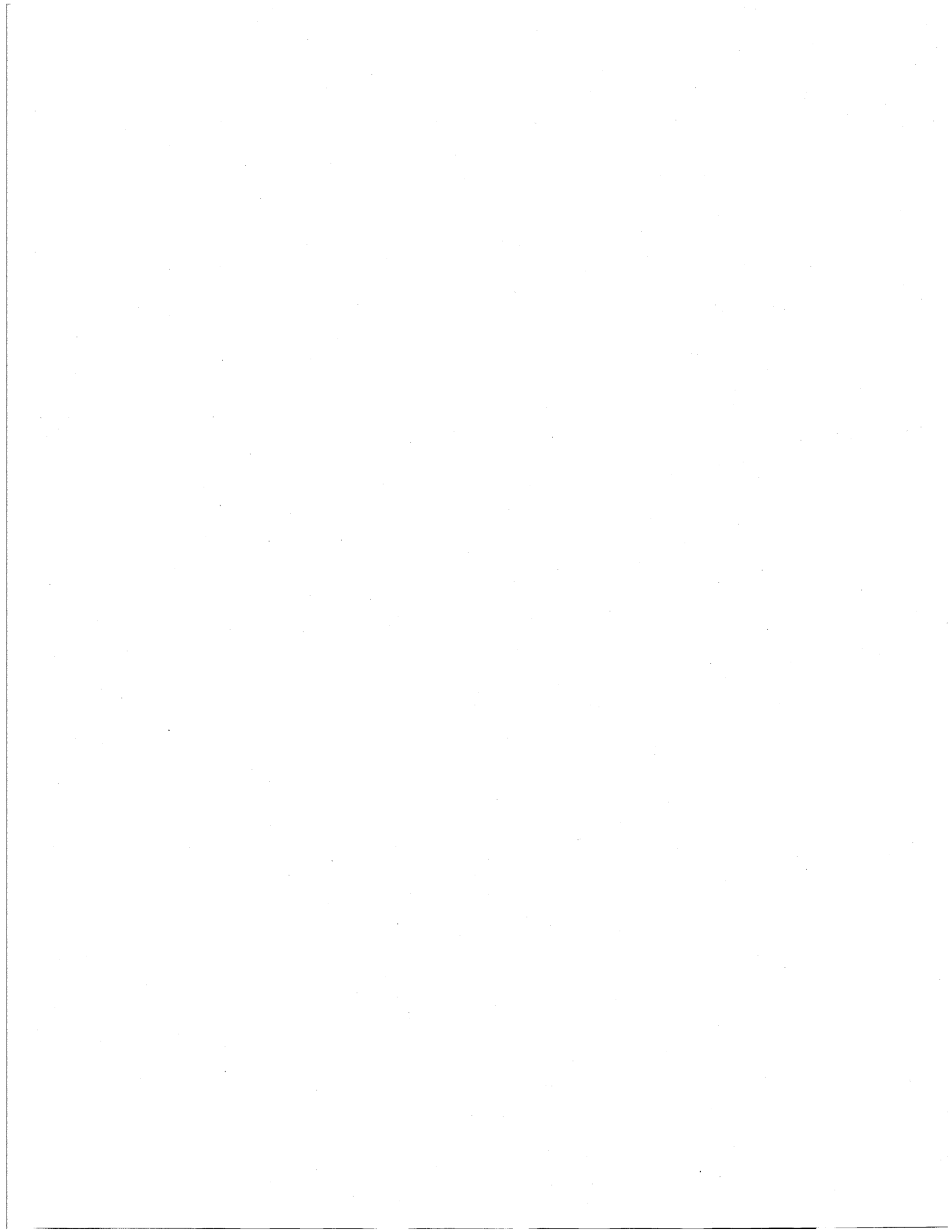
Table a. Numerical value of the coefficients b_{ij}

$i=$	0	1	2	3	4	5
$j=0$	0.501 938	0.162 888	−0.130 356	0.907 919	−0.551 119	0.146 543
1	0.235 622	0.789 393	0.673 665	1.207 552	0.067 0665	−0.084 3370
2	−0.274 637	−0.743 539	−0.959 456	−0.687 343	−0.497 089	0.195 286
3	0.145 831	0.263 129	0.347 247	0.213 486	0.100 754	−0.032 932
4	−0.027 0448	−0.025 3093	−0.026 7758	−0.082 2904	0.060 2253	−0.020 2595

in density, which corresponds to an approximate pressure range

$$0 < P < 100 \text{ MPa};$$

its domain of validity can be extended to

$$P = 1000 \text{ MPa in the range } 0 < t < 100 \text{ °C}$$

$$P = 350 \text{ MPa in the range } 100 \text{ °C} < t < 560 \text{ °C}.$$

The equation adopted in this Appendix is not the only possible interpolation formula. An alternative form was given in the paper, "Correlation of Viscosity for Water and Steam", by A. Nagashima, M. Ikeda, and I. Tanishita, Proc. Eighth ICPS, Giens, France, 1974.

Appendix D

Viscosity of Compressed Water and Superheated Steam

Viscosity in μPa s ($\equiv 10^{-6}$ kg/m s)
Pressure P in MPa
Temperature t in °C.

(Smoothed values obtained with the aid of eqs (1) and (2) of Appendix C together with the constants listed therein, and density values based on the 1968 IFC Formulation for Scientific and General Use.)

Appendix D

Dynamic Viscosity of Water and Steam

(Same as table 6 in text)

Appendix E

Special Committee Membership

Dr. A. A. Aleksandrov	(USSR)
Dr. P. Bury	(France)
Prof. J. Kestin	(USA)
Prof T. Minamiyama	(Japan)
Prof. A. Nagashima	(Japan)
Dr. M. Reimann	(FRG)
Mr. K. Scheffler	(FRG)
Dr. J. Straub	(FRG)
Prof. A. A. Tarzimanov	(USSR)
Prof D. Vodar	(France)
Prof. J. V. Sengers	(USA)
Mr. J. Yata	(Japan)

Appendix II

Equation of the Viscosity of Water at Atmospheric Pressure in the Range 0–100 °C

The following simplified equation gives the viscosity of water at atmospheric pressure in the range 0–100 °C as listed in table II-1. Agreement with selected experimental data is shown in figure II-1.

$$\mu = A \exp\left[\frac{1 + BT}{CT + DT^2}\right] \tag{II-1}$$

Constants

$$A = 0.12571873 \times 10^{-1}$$
$$B = -0.58064362 \times 10^{-2}$$
$$C = 0.11309108 \times 10^{-2}$$
$$D = -0.57239520 \times 10^{-5}$$

Units

μ dynamic viscosity 10^{-3} Pa·s
T temperature K

Table II-I. Viscosity of water at atmospheric pressure calculated with the aid of eq (II-1) (10^{-3} Pa·s)

| t (°C)	0	1	2	3	4	5	6	7	8	9
0	1.79190	1.73148	1.67421	1.61987	1.56828	1.51923	1.47258	1.42815	1.38582	1.34545
10	1.30693	1.27013	1.23496	1.20132	1.16912	1.13828	1.10873	1.08039	1.05319	1.02708
20	1.00200	0.97789	0.95470	0.93239	0.91091	0.89021	0.87027	0.85104	0.83250	0.81460
30	0.79732	0.78062	0.76449	0.74890	0.73381	0.71922	0.70510	0.69142	0.67818	0.66534
40	0.65290	0.64084	0.62914	0.61778	0.60676	0.59606	0.58567	0.57557	0.56576	0.55622
50	0.54695	0.53793	0.52915	0.52061	0.51230	0.50420	0.49631	0.48863	0.48115	0.47385
60	0.46674	0.45980	0.45303	0.44643	0.43999	0.43371	0.42757	0.42158	0.41573	0.41001
70	0.40442	0.39897	0.39363	0.38842	0.38332	0.37833	0.37345	0.36868	0.36401	0.35944
80	0.35497	0.35059	0.34630	0.34210	0.33799	0.33396	0.33001	0.32614	0.32235	0.31863
90	0.31499	0.31142	0.30791	0.30448	0.30111	0.29780	0.29456	0.29137	0.28825	0.28518
100	0.28217	0.27921	0.27631	0.27346	0.27066	0.26791	0.26521	0.26255	0.25994	0.25738
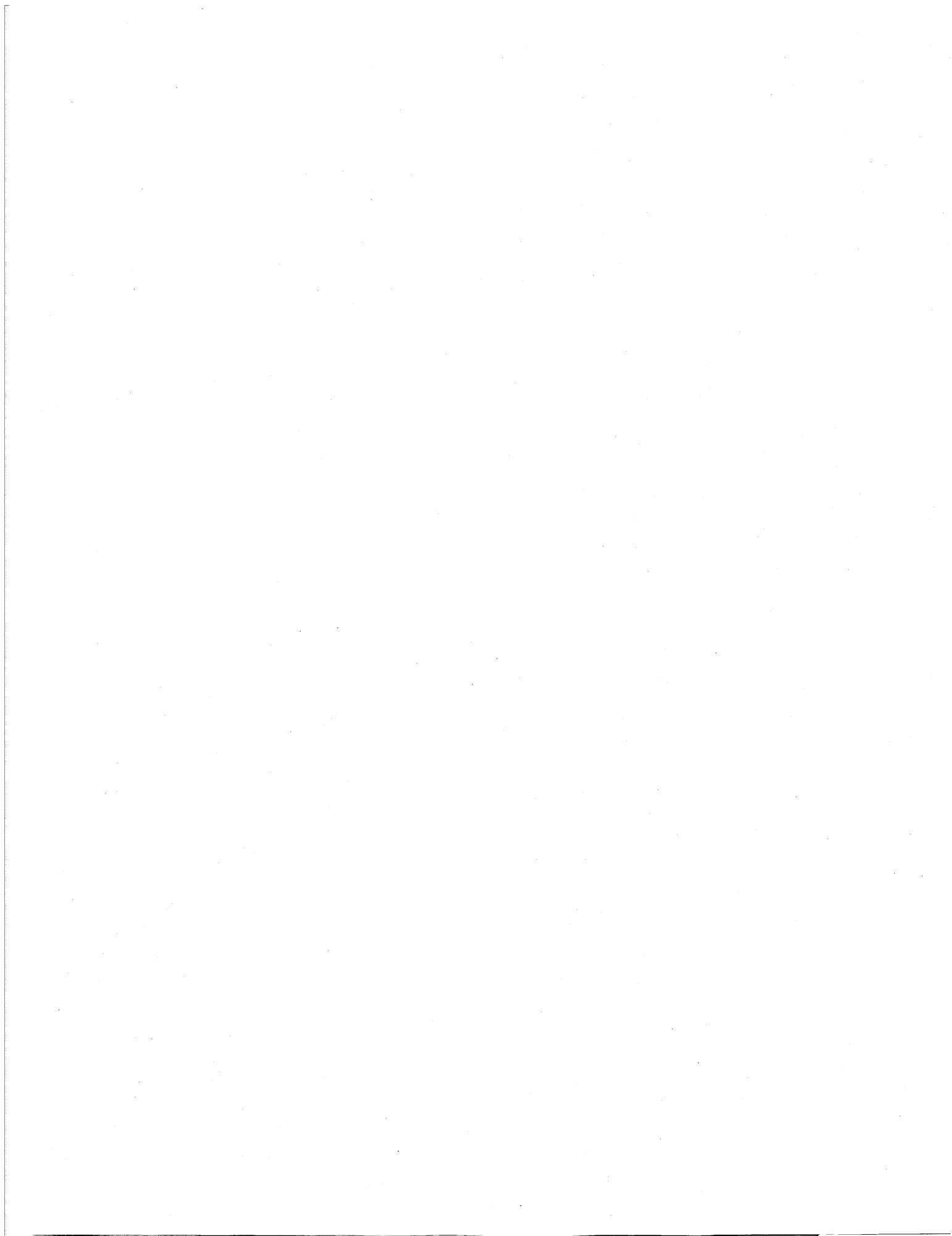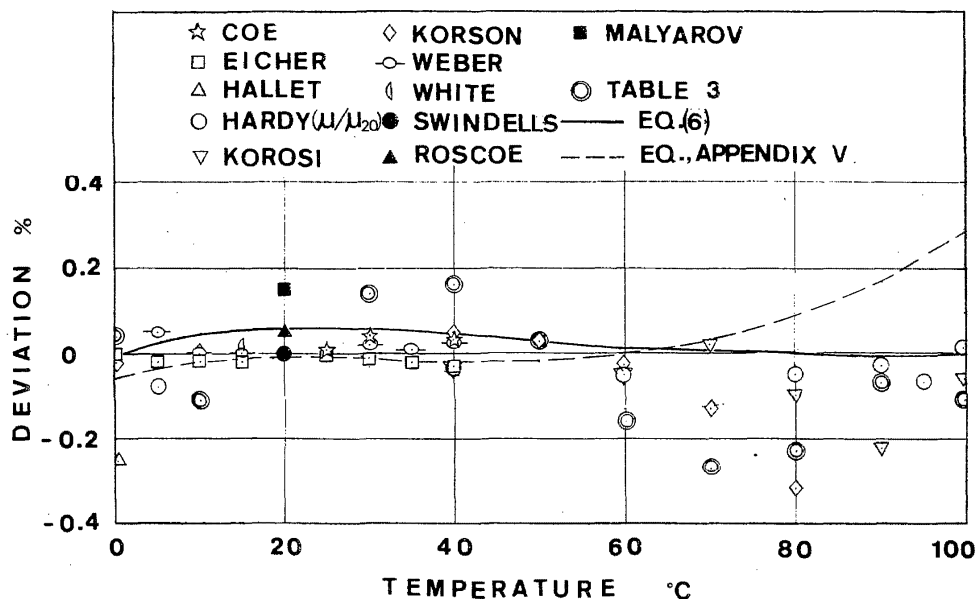
FIGURE II-1. Comparison of selected data with eq (II-1)

Appendix III

Deleted or Corrected Experimental Data

Deleted: ref. [43]* 392.2 °C, 31.617 MPa
             595.0 °C, 60.55 MPa

      ref. [97] 385.5 °C, 351 atm
                384 °C,   301 atm
                600.5 °C, 296.5 atm
                600 °C,   254 atm
                382 °C,   254 atm
                380 °C,   251 atm
                362.7 °C, 209 atm
                357.2 °C, 203 atm
                all data on saturation line

      ref. [44] 650 °C,   28.7 atm
                700 °C,   31.1 atm

      ref. [98] 487 °C,   700 atm
                388 °C,   700 atm
                478.6 °C, 400 atm

---
* Numbers in brackets indicate references in the text.

          477 °C,   300 atm
          473.3 °C, 300 atm
          423 °C,   300 atm
          383.6 °C, 250 atm
          382.7 °C, 250 atm
          382.9 °C, 250 atm

Corrected: ref. [97] 525.5 °C, 96.5 atm to 396.6 atm
                    530.6 °C, 105.0 atm, 10.2 $\times$
                      10 cm^2/s to 102 $\times$ 10 cm^2/s

      ref. [98] 367.5 °C, 200 atm, 570 μP to
                    270 μP

      ref. [52] 18.4 °C, 381.5 atm
                17.0 °C, 655.5 atm
                some more misprints

      ref. [53] 155.0 bar, 0.59268 g/cm^3 to
                    155.6 bar 0.59316 g/cm^3
                155.0 bar, 0.59263 g/cm^3 to
                    155.6 bar 0.59311 g/cm^3
                154.9 bar, 0.59225 g/cm^3 to
                    155.7 bar 0.59289 g/cm^3

Appendix IV

Specific Volume of Water Substance Calculated with the Aid of the 1968 IFC Formulation

Units: P/MPa, t/deg. C, V/(liter/kg)

P	0.0	25.0	50.0	75.0	100.0	150.0
0.1	1.00017	1.00285	1.01208	1.02591	1696.39990	1936.59985
0.5	0.99997	1.00267	1.01190	1.02572	1.04350	1.09077
1.0	0.99972	1.00244	1.01167	1.02549	1.04324	1.09042
2.5	0.99897	1.00177	1.01100	1.02477	1.04245	1.08938
5.0	0.99773	1.00065	1.00989	1.02360	1.04116	1.08767
7.5	0.99649	0.99955	1.00879	1.02243	1.03988	1.08598
10.0	0.99527	0.99845	1.00770	1.02128	1.03861	1.08432
12.5	0.99405	0.99736	1.00662	1.02014	1.03736	1.08268
15.0	0.99283	0.99628	1.00554	1.01901	1.03612	1.08107
17.5	0.99163	0.99520	1.00443	1.01789	1.03489	1.07948
20.0	0.99043	0.99414	1.00342	1.01677	1.03368	1.07790
22.5	0.98924	0.99308	1.00238	1.01567	1.03248	1.07635
25.0	0.98806	0.99203	1.00134	1.01458	1.03129	1.07482
27.5	0.98688	0.99098	1.00031	1.01350	1.03011	1.07331
30.0	0.98572	0.98994	0.99928	1.01243	1.02894	1.07182
35.0	0.98341	0.98789	0.99726	1.01031	1.02664	1.06889
40.0	0.98113	0.98586	0.99527	1.00823	1.02438	1.06602
45.0	0.97888	0.98386	0.99330	1.00618	1.02216	1.06323
50.0	0.97667	0.98188	0.99137	1.00416	1.01998	1.06049
55.0	0.97449	0.97993	0.98946	1.00217	1.01783	1.05782
60.0	0.97234	0.97800	0.98757	1.00021	1.01572	1.05519
65.0	0.97023	0.97609	0.98571	0.99828	1.01365	1.05263
70.0	0.96815	0.97421	0.98387	0.99638	1.01160	1.05011
75.0	0.96610	0.97235	0.98205	0.99450	1.00959	1.04763
80.0	0.96410	0.97050	0.98026	0.99265	1.00761	1.04521
85.0	0.96213	0.96868	0.97848	0.99082	1.00565	1.04282
90.0	0.96020	0.96688	0.97673	0.98901	1.00372	1.04048
95.0	0.95831	0.96510	0.97500	0.98723	1.00182	1.03818
100.0	0.95646	0.96334	0.97328	0.98546	0.99994	1.03591

Units: P/MPa, t/deg. C, V/(liter/kg)

P	t 200.0	250.0	300.0	350.0	375.0	400.0
0.1	2172.39990	2406.09985	2638.79980	2870.89990	2986.79980	3102.59985
0.5	424.98999	474.39990	522.57983	570.10986	593.71997	617.25000
1.0	205.93999	232.71999	257.95996	282.46997	294.54980	306.55981
2.5	1.15551	87.00999	98.92000	109.75999	114.95999	120.06999
5.0	1.15296	1.24941	45.32399	51.94398	54.93300	57.79599
7.5	1.15045	1.24493	26.71300	32.42599	34.76399	36.92999
10.0	1.14801	1.24061	1.39780	22.42099	24.53499	26.40599
12.5	1.14561	1.23644	1.38750	16.12799	18.25099	20.00600
15.0	1.14326	1.23241	1.37790	11.48500	13.89500	15.65500
17.5	1.14095	1.22851	1.36900	1.71500	10.56500	12.45600
20.0	1.13869	1.22473	1.36060	1.66580	7.69510	9.95200
22.5	1.13647	1.22107	1.35270	1.62940	2.44900	7.86900
25.0	1.13429	1.21751	1.34530	1.60010	1.97630	6.00930
27.5	1.13215	1.21405	1.33820	1.57550	1.86090	4.20500
30.0	1.13005	1.21068	1.33150	1.55420	1.79140	2.80600
35.0	1.12596	1.20421	1.31900	1.51860	1.70230	2.10720
40.0	1.12199	1.19805	1.30760	1.48950	1.64270	1.91070
45.0	1.11815	1.19218	1.29710	1.46470	1.59770	1.80400
50.0	1.11443	1.18657	1.28730	1.44320	1.56150	1.73200
55.0	1.11081	1.18119	1.27810	1.42420	1.53120	1.67810
60.0	1.10729	1.17603	1.26950	1.40720	1.50510	1.63510
65.0	1.10387	1.17106	1.26150	1.39170	1.48230	1.59930
70.0	1.10053	1.16628	1.25380	1.37760	1.46190	1.56870
75.0	1.09728	1.16166	1.24650	1.36460	1.44360	1.54210
80.0	1.09410	1.15719	1.23960	1.35250	1.42700	1.51840
85.0	1.09100	1.15286	1.23300	1.34130	1.41180	1.49720
90.0	1.08797	1.14866	1.22670	1.33070	1.39770	1.47800
95.0	1.08500	1.14459	1.22070	1.32080	1.38470	1.46050
100.0	1.08210	1.14063	1.21480	1.31140	1.37250	1.44440

Units: P/MPa, t/deg. C, V/(liter/kg)

P	425.0	450.0	475.0	500.0	550.0	600.0
0.1	3218.39990	3334.09985	3449.79980	3565.39990	3796.59985	4027.69995
0.5	640.71997	664.13989	687.51978	710.89990	757.45996	803.98999
1.0	318.50000	330.37988	342.22998	354.03979	377.56982	401.01978
2.5	125.10999	130.09000	135.03000	139.92999	149.62000	159.23999
5.0	60.56799	63.27100	65.92000	68.52599	73.63100	78.64000
7.5	38.97899	40.94398	42.84599	44.69800	48.28899	51.76999
10.0	28.12500	29.73999	31.28099	32.76500	35.60899	38.33299
12.5	21.55899	22.98399	24.31999	25.59099	27.99500	30.26799
15.0	17.13300	18.44899	19.65999	20.79500	22.91399	24.89000
17.5	13.92400	15.18200	16.31400	17.35899	19.28000	21.04799
20.0	11.46800	12.70600	13.78800	14.77200	16.55099	18.16499
22.5	9.50700	10.75400	11.81000	12.75200	14.42500	15.92200
25.0	7.88440	9.16810	10.21500	11.12900	12.72200	14.12800
27.5	6.50010	7.84900	8.89900	9.79500	11.32800	12.66000
30.0	5.29620	6.73040	7.79400	8.67950	10.16500	11.43700
35.0	3.43810	4.95360	6.04730	6.92230	8.33930	9.51800
40.0	2.53920	3.69520	4.75770	5.61490	6.97660	8.08470
45.0	2.18840	2.91550	3.82140	4.62960	5.93000	6.97840
50.0	2.00940	2.48730	3.17370	3.89070	5.11190	6.10410
55.0	1.89680	2.24220	2.74820	3.34590	4.46620	5.40140
60.0	1.81700	2.08560	2.46980	2.95200	3.95390	4.82960
65.0	1.75610	1.97570	2.28010	2.66900	3.53650	4.36020
70.0	1.70730	1.89330	2.14360	2.46250	3.22240	3.97220
75.0	1.66670	1.82850	2.04030	2.30770	2.96440	3.64980
80.0	1.63200	1.77560	1.95910	2.18790	2.75840	3.38080
85.0	1.60180	1.73130	1.89310	2.09240	2.59240	3.15550
90.0	1.57510	1.69330	1.83810	2.01440	2.45680	2.96610
95.0	1.55120	1.66010	1.79140	1.94920	2.34380	2.80590
100.0	1.52960	1.63070	1.75090	1.89370	2.24820	2.66930
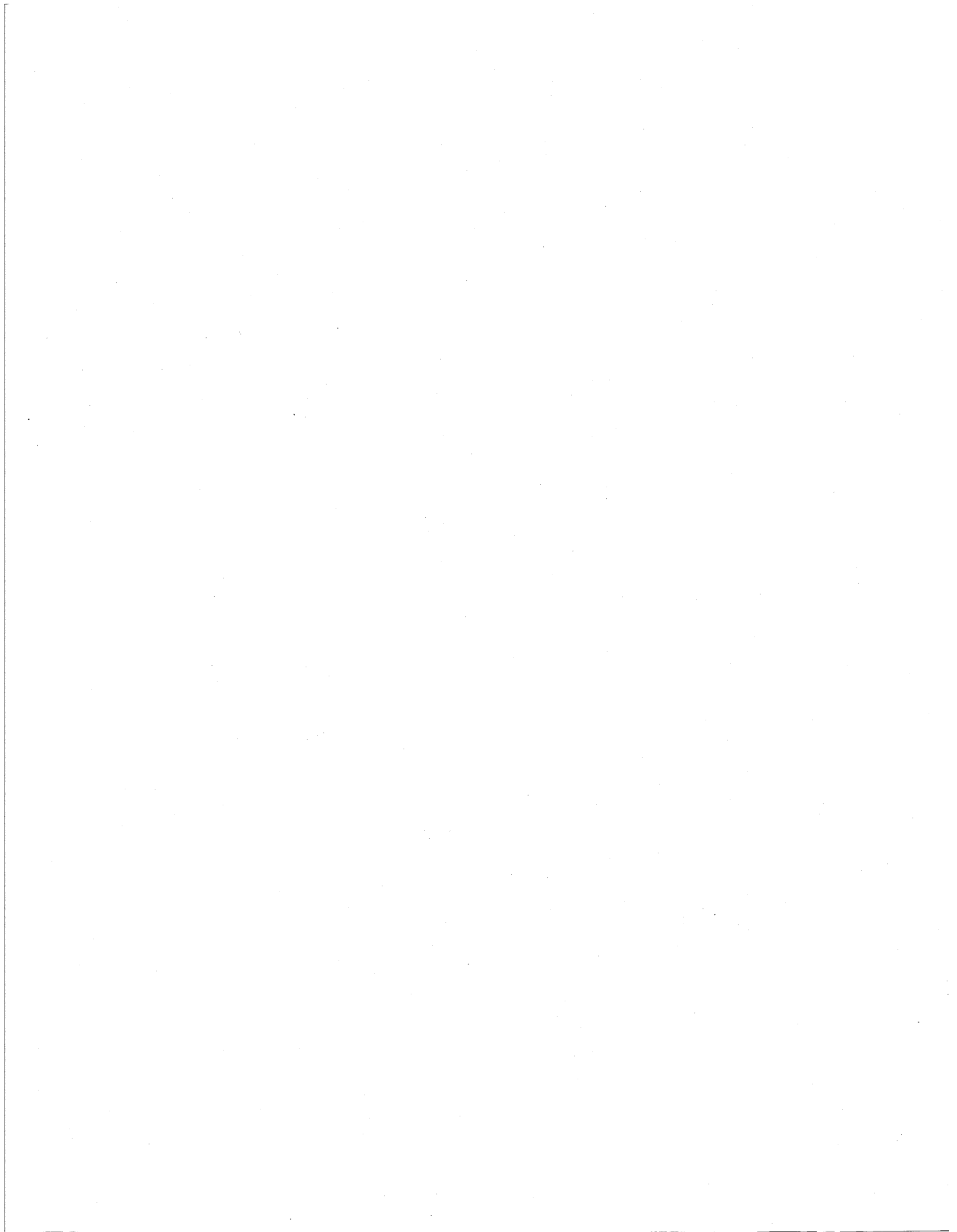
Units: P/MPa, t/deg. C, V/(liter/kg)

P	650.0	700.0	750.0	800.0
			t	
0.1	4258.79688	4489.79688	4720.79688	4951.69922
0.5	850.44995	896.86987	943.25000	989.58984
1.0	424.40991	447.75000	471.05981	494.31982
2.5	168.78999	178.28000	187.73999	197.17000
5.0	83.57700	88.45999	93.31000	98.12000
7.5	55.17499	58.52399	61.83099	65.10199
10.0	40.97400	43.55699	46.09499	48.59799
12.5	32.45299	34.57700	36.65599	38.69699
15.0	26.77399	28.59200	30.36400	32.09900
17.5	22.71700	24.31898	25.87199	27.38699
20.0	19.67499	21.11499	22.50400	23.85500
22.5	17.31000	18.62399	19.88599	21.10899
25.0	15.41800	16.63199	17,79300	18.91399
27.5	13.87200	15.00400	16.08199	17.11899
30.0	12.58400	13.64900	14.65800	15.62500
35.0	10.56300	11.52200	12.42300	13.28000
40.0	9.05360	9.93300	10.75100	11.52600
45.0	7.88570	8.70200	9.45600	10.16600
50.0	6.95870	7.72300	8.42500	9.08200
55.0	6.20830	6.92800	7.58600	8.19900
60.0	5.59170	6.27200	6.89100	7.46700
65.0	5.07890	5.72200	6.30900	6.85200
70.0	4.64850	5.25800	5.81400	6.32800
75.0	4.28440	4.86200	5.38900	5.87800
80.0	3.97440	4.52100	5.02300	5.48800
85.0	3.70910	4.22600	4.70300	5.14600
90.0	3.48080	3.96900	4.42300	4.84600
95.0	3.28350	3.74400	4.17700	4.58100
100.0	3.11210	3.54700	3.95800	4.34500

Appendix V

Alternative Interpolation Equation

The IAPS Release on viscosity reproduced as Appendix I mentions an alternative interpolation equation for the new skeleton table. This was prepared by Nagashima, Ikeda and Tanishita [129] and is reproduced below*; it is introduced for use in conjunction with the 1967 IFC Formulation [113]:

$$\frac{\mu}{10^{-7}\text{Pa} \cdot \text{s}} = \frac{\mu_1}{10^{-7}\text{Pa} \cdot \text{s}} \qquad (V\text{-}1)$$

$$+ B(\tau) \frac{\rho}{10^3 \text{kg/m}^3} + C(\tau) \frac{\rho^2}{(10^3 \text{kg/m}^3)^2}$$

$$+ D(\tau) \frac{\rho^2}{(10^3 \text{kg/m}^3)^2} \ln \frac{\rho}{10^3 \text{kg/m}^3}$$

where

$$\mu_1 = \sum_{i=0}^{4} a_i \tau^i$$

$$B(\tau) = \sum_{i=0}^{3} b_i \tau^i$$

* Several constants were slightly modified from those in ref. [129] in order to get better agreement with experimental data at 0 °C.

$$C(\tau) = \exp\left(\sum_{i=0}^{5} c_{1i} \tau^i + c_{16} \tau^{-15} + c_{17} \tau^{-20}\right)$$

$$+ \sum_{i=0}^{4} c_{2i} \tau^i + c_{30} \tau^{25}$$

$$D(\tau) = \sum_{i=0}^{2} d_i \tau^i + d_3 \tau^{-13} + d_4 \tau^{16}$$

$$\tau = T/100 \text{ K}$$

The constants are listed in table V-1.
Range of validity.

Temperature range: 273.15—1273.15 K

Pressure range: saturation pressure or 0.1 MPa to 120 MPa.

A detailed comparison between the ultimately sanctioned eq (6) in the text and eq (V-1) above was performed by a study group at the Engineering University of Hanover**. This revealed that the differences in the output of the two equations were insignificant over most of the region covered, except for the neighborhood of the critical point. Both equations are based on the primary data referred to in table 2 but eq (6) seems to be closer

** Borman, H. Untersuchung von Gleichungen zur Berechnung der dynamischen Viskositaet von Wasserdampf, T. U. Hannover, (1974). Actually the comparison was performed between the earlier versions of eq (6) and eq (V-1), but modifications of the equations were so small that this comparison could be regarded as the comparison between eq (6) and eq (V-1).
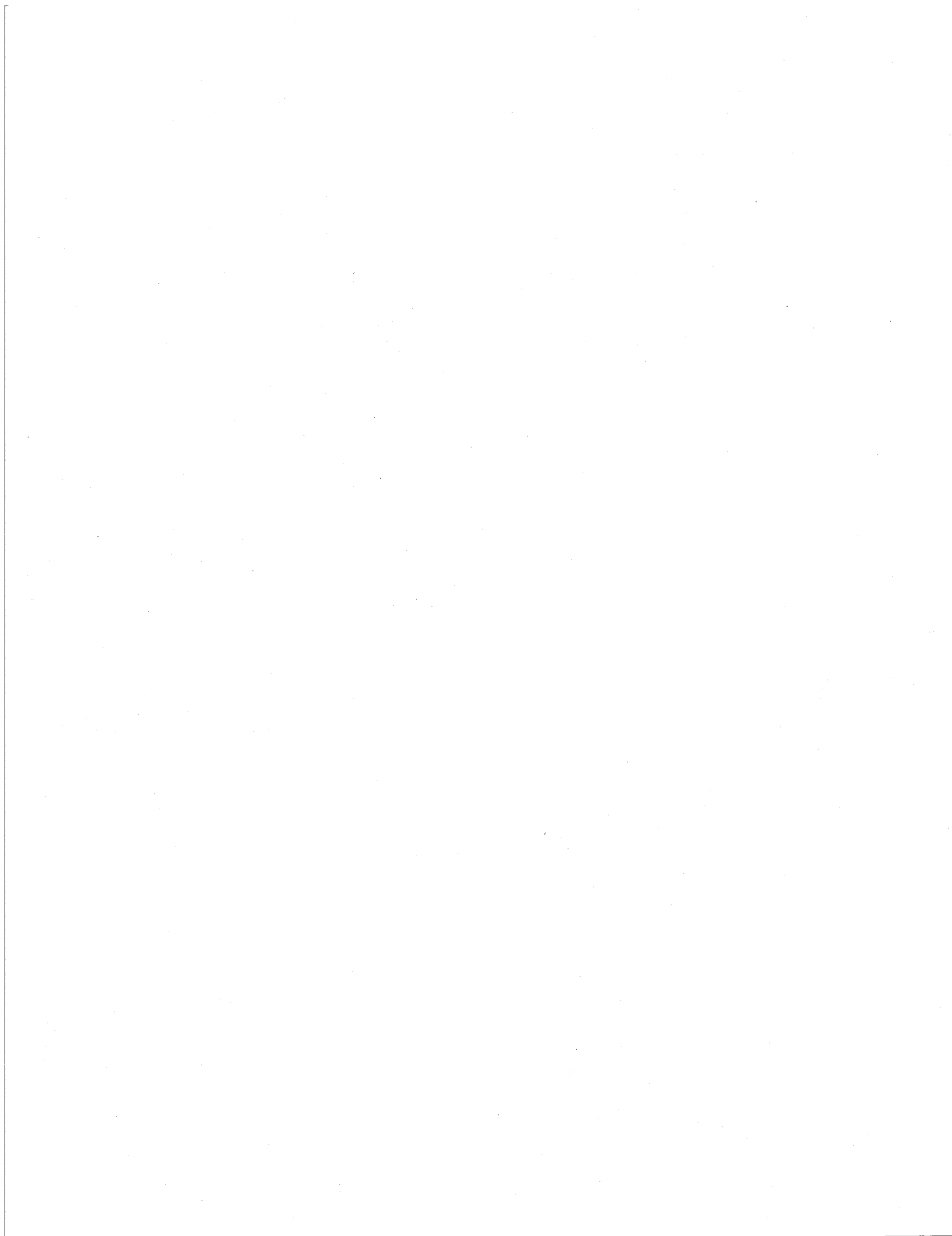
to several specially favored investigations, whereas eq (V–1) represents a more even-handed compromise.

The differences between the two equations are insignificant for industrial applications over most of the region, as already mentioned, but in the liquid phase over the interval 300°C – 370 °C eq (6) gives values which are about 2% lower than those of eq (V–1). Similarly in the steam phase around 700 °C and 70 MPa eq (6) leads to values which are higher by about 2%.

Figure V–1 gives a sample comparison between the two equations at 300 °C over the entire density range. Figures V–2 and V–3 correspond to figures 4 and 5 in the text and underline the systematic difference between two sets of experimental data pertaining to the steam region. Figures 2 and 13 in the text may also be consulted for further comparisons.

TABLE V–1. Constants in equation (V–1)

|			
a_0	$- 2.7339277 \times 10^0$	c_{15}	$- 6.054365973 \times 10^{-2}$
a_1	2.4932052×10^1	c_{16}	$- 1.246534018 \times 10^5$
a_2	2.9401648×10^0	c_{17}	2.573362773×10^7
a_3	$- 2.0047725 \times 10^{-1}$	c_{20}	5.5771181×10^3
a_4	3.6958643×10^{-3}	c_{21}	$- 1.1829911 \times 10^3$
		c_{22}	1.2445541×10^2
b_0	$- 6.2282739 \times 10^3$	c_{23}	$- 9.7244183 \times 10^0$
b_1	2.1383753×10^3	c_{24}	4.4407387×10^{-1}
b_2	$- 2.4704586 \times 10^2$	c_{30}	$1.5965315 \times 10^{-24}$
b_3	9.7297515×10^0		
		d_0	1.8249871×10^3
c_{10}	9.472090038×10^1	d_1	$- 5.9527300 \times 10^2$
c_{11}	$- 9.557980366 \times 10^1$	d_2	3.7666667×10^1
c_{12}	4.393184560×10^1	d_3	$- 3.1874983 \times 10^{10}$
c_{13}	$- 1.039644510 \times 10^1$	d_4	$1.3573211 \times 10^{-14}$
c_{14}	1.246223348×10^0		
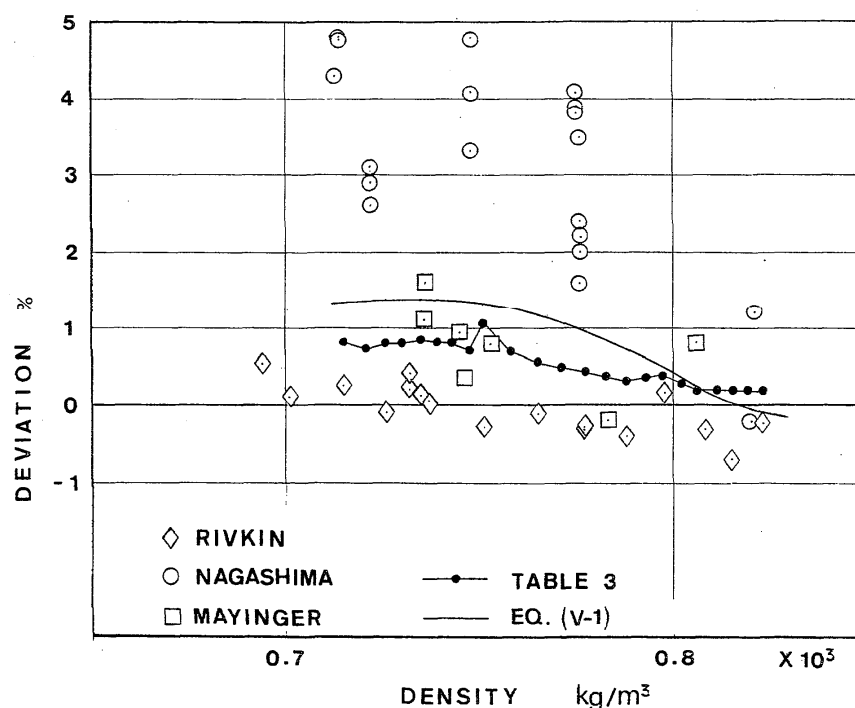
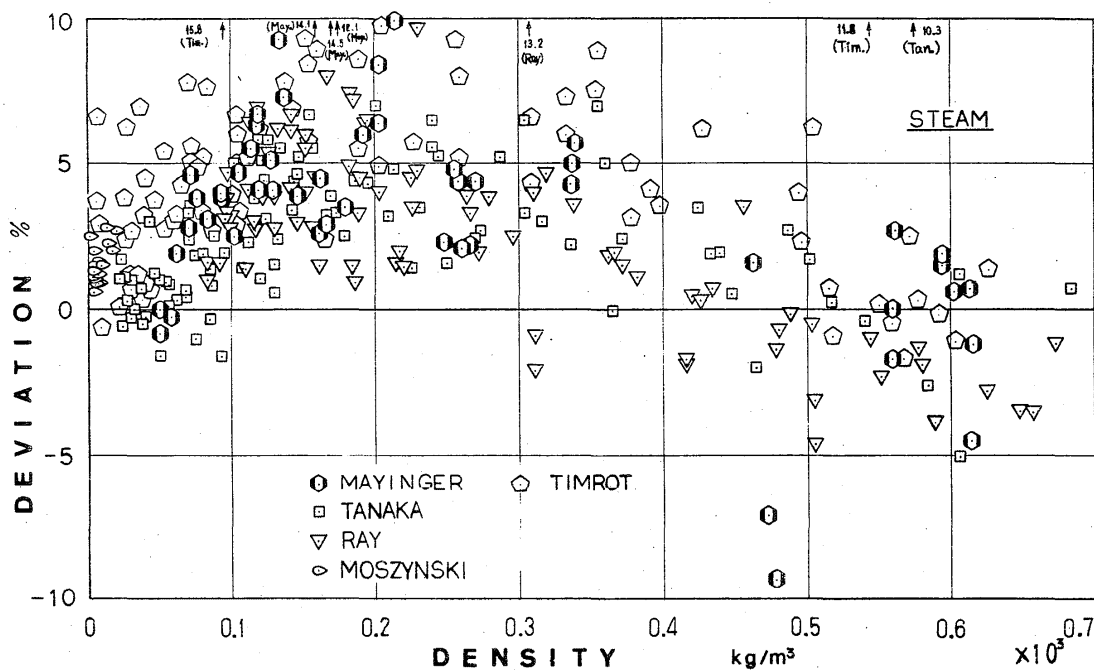FIGURE V–1. Comparison of correlations and experimental data with eq (6)

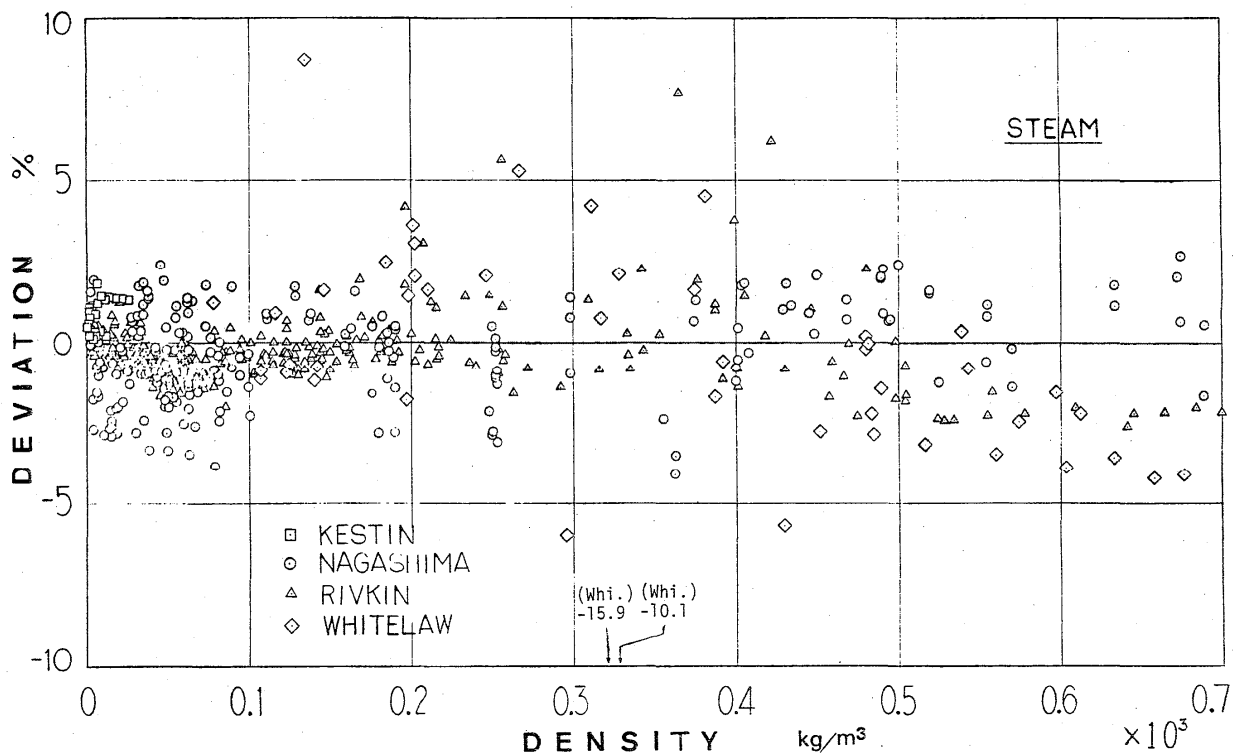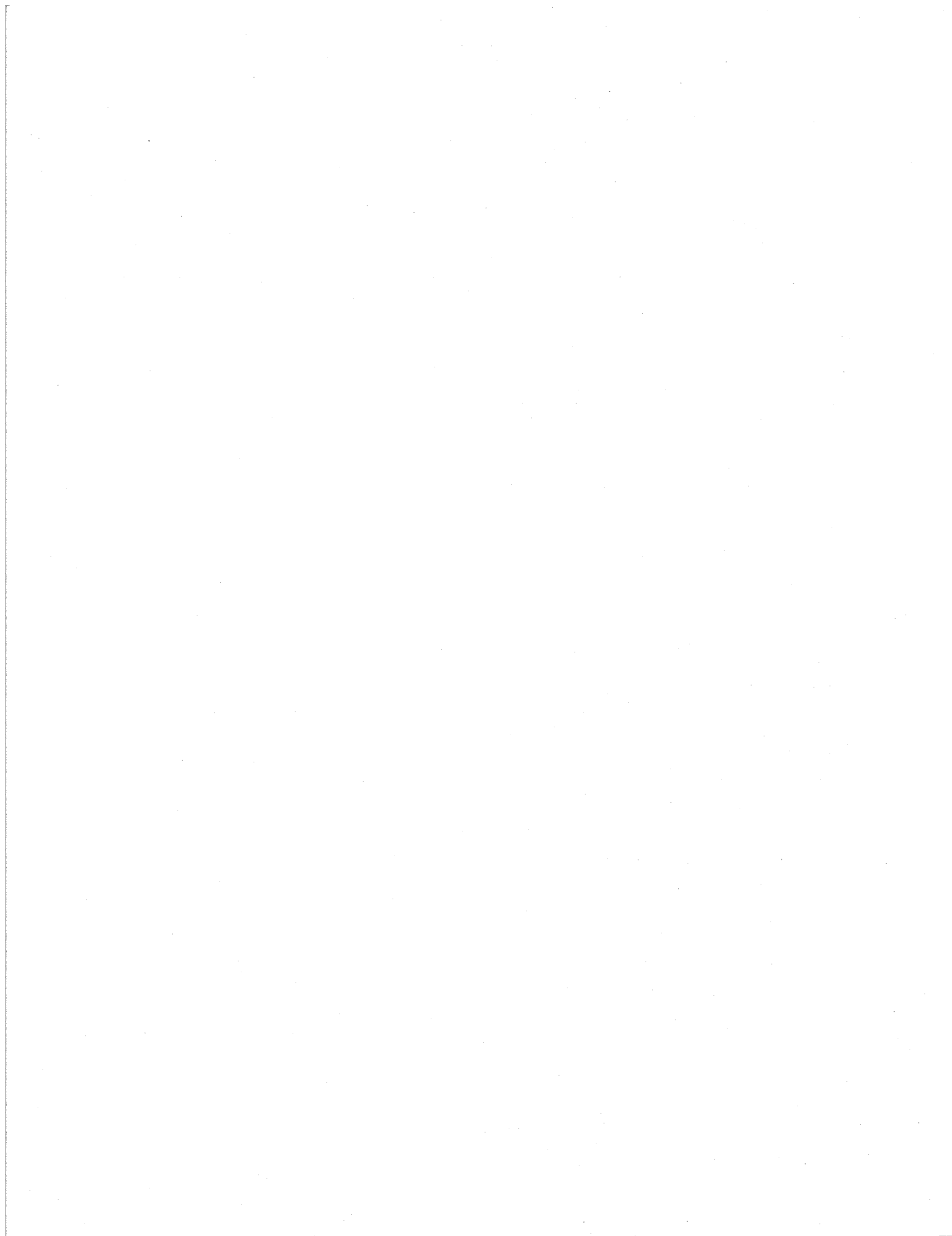FIGURE V-2. Deviations of measured data from the equation (V-1)

FIGURE V-3. Deviations of measured data from the equation (V-1)

Appendix VI

Effect of the Different Density Sources

The viscosity equation, eq (6) in the text, was recommended to be used with the 1968 IFC Formulation, although the most-widely-used equation of state for water substance in the world is 1967 IFC Formulation. Table VI-1 shows some examples of effect of different density sources on the calculated viscosity data.

TABLE VI-1

t °C	P MPa	$\mu(\rho_{1968})$ [a] 10^{-6} Pa·s	$\mu(\rho_{1967})$ [b] 10^{-6} Pa·s	Deviation [c]
350	70.0	88.9	88.7	−0.2
	80.0	91.4	91.1	−0.3
	90.0	93.7	93.4	−0.3
	100.0	95.9	95.5	−0.4
375	22.5	47.4	46.5	−2.2
	25.0	58.2	58.0	−0.3
	27.5	61.9	61.8	−0.2
	80.0	85.0	84.8	−0.2
	90.0	87.5	87.3	−0.2
	100.0	89.9	89.5	−0.4
400	27.5	33.62	33.76	+0.4
	30.0	43.67	43.38	−0.7
	90.0	81.7	81.6	−0.1
	100.0	84.2	84.0	−0.2
425	35.0	39.26	39.39	+0.3
	40.0	48.62	48.48	−0.3
450	40.0	39.03	39.15	+0.3

[a] Equation (6) + the 1968 IFC Formulation.
[b] Equation (6) + the 1967 IFC Formulation.

[c] Deviation $-\dfrac{\mu(\rho_{1967}) - \mu(\rho_{1968})}{\mu(\rho_{1968})} \times 100$.