

REPORT OF SCOR WORKING GROUP 10
UNESCO/SCOR/IAPSO/ICES JOINT PANEL
ON OCEANOGRAPHIC TABLES AND STANDARDS
Report of Meeting in Kiel, 10-12 December 1969

The meeting was held in the Institute for Applied Physics, University of Kiel, with the following members in attendance:

F. Hermann (Chairman), O. Saelen, F. Culkin, N.P. Fofonoff, W. Kroebel, K. Grasshoff, F. Fisher, M. Menache.

Dr. G.N. Ivanoff-Frantzkevich was unable to attend. The following observers were present:

G. Giermann (UNESCO), K. Kremling (Inst. für Meereskunde), W.S. Wooster (SCOR).

Refractive Index

Dr. Culkin referred to the work of Dr. J.S.M. Rusby published in Deep-Sea Research (vol. 14, pp. 427-439, 1967); the results have been incorporated in the International Oceanographic Tables. Although it would be useful to have these measurements confirmed, the Panel was unable to propose someone to repeat the measurements with the same high precision. With publication of the tables, the Panel considered its task in this area to be fulfilled.

Dissolved Oxygen

As proposed by the Panel during its meeting in Bern, the ICES Subcommittee on Chemical Analysis of Sea Water was asked to recommend further steps with respect to oxygen solubility tables. The ICES group in 1967 recommended the smoothing equation of E.J. Green as the basis for such tables. In the meantime, new independent measurements of oxygen solubility in sea water have been made by J. Carpenter and by J.P. Riley. These new measurements agree well with each other but differ somewhat from those of Green.

A meeting of specialists concerned with the question was convened in Fort Lauderdale in February 1969, by SCOR and the U.S. National Academy of Science Committee on Oceanography. The following participated:

D.E. Carritt (Chairman), B. Benson, E.J. Green, J.L. Carpenter, J. Gieskes, J.P. Riley, K. Grasshoff.

At this meeting, it was concluded that the raw data - after some correction to Green's measurements - agreed well and that no significant differences could be found despite the fact that very different techniques had been used. It was decided that each experimenter should apply his own technique of smoothing and interpolation to the set of all raw data. Experimental values departing from the curve by more than ± 0.03 ml/l should be rejected, and the smoothing should be repeated using the remaining data. These calculations should be submitted to Professor Carritt not later than the fall of 1969. It was not felt that new measurements would improve significantly the reliability of the existing data.

Unfortunately, the recalculated saturation values were not submitted in time for a comparison of the different treatments to be made at the Kiel meeting.

Meanwhile, R. Weiss (Scripps Institution of Oceanography) developed a simple equation for smoothing the experimental data of Carpenter and Riley. The equation has a sound thermo-

dynamical basis, being derived from the Vant' Hoff equation for the dependence of the Bunsen solubility coefficient on temperature and from the Setchenof equation for the salinity dependence. The equation has the form

$$\ln c = A_1 + A_2 \frac{100}{T} + A_3 \ln\left(\frac{T}{100}\right) + A_4 \frac{T}{100} + S^{\circ}/\text{‰} (B_1 + B_2 \frac{T}{100} + B_3 \frac{T^2}{10^4})$$

and gives a mean standard deviation from the experimental data, depending on the source of data, of ± 0.018 ml/l or ± 0.016 ml/l.

The Panel considered this equation the best now available for calculation of the new saturation tables. Therefore, it was decided to send a copy of Weiss' preliminary paper to participants of the Fort Lauderdale meeting asking for comments by January 1970. It should then be possible to calculate the new tables by April and forward them to UNESCO in May.

Specific Gravity

Dr. Culkin gave a final report on the measurements of the specific gravity of sea water as a function of temperature and salinity. These measurements are the basis of new tables to be published by UNESCO. In a discussion of format, the Panel considered most convenient that used by the U.S. Navy Oceanographic Office for the determination of sigma-t from temperature and salinity.

Confirmation of the basic N.I.O. measurements by an independent laboratory was considered desirable, but the Panel could not suggest one being able to do this with the same accuracy. In this connection, Dr. Kremling mentioned a new densitometer¹ available in Kiel by which specific gravity can be determined with a precision of ± 3 in the 3d decimal of sigma-t. Measurement is made of the Eigenfrequency of a glass capillary filled with the sample; each determination takes about ten minutes. Preliminary comparisons with NIO measurements have been made with this instrument, with good results.

Before the final edition of the UNESCO tables, the Panel recommended that the silicate content of the reference water be checked. Attention should be paid to the results of Russian studies of the specific gravity - temperature - salinity relationship. Mr. Crease (British Oceanographic Data Center) should be approached by Mr. Culkin for calculation and interpolation of the new tables, in cooperation with Drs. Fofonoff and Fisher. As suggested by Mr. Menache, the new temperature scale should be used.

The Panel discussed the need to compare actual measurements of specific gravity of water samples randomly selected from all parts of the world ocean with sigma-t values for the same samples calculated from temperature and salinity determined by conductivity measurement. Such measurements now seemed feasible with the new precision instrument available in Kiel. The Panel recommended that all necessary support be given Dr. Kremling for making such measurements. Dr. Kremling will approach several institutions for obtaining appropriate samples. He was also asked to perform some independent cross checks on N.I.O. samples.

Isotopic Composition

Mr. Menache reported on measurements of the isotopic composition of reference water distilled according to N.I.O. procedure from deep (about 2000 m) water of the western Mediterranean. Using samples supplied by N.I.O. and by the Institut für Meereskunde, Kiel, there appeared to be no significant difference between isotopic composition of the original water and that of the distillates. The distillation procedure can then be recommended as a standard pro-

1) Model DMA02, Anton Paar KG, A-8054 Graz, Postfach 17, Austria

cedure for obtaining reference water for the determination of specific gravity. In this connection, adoption of the new temperature scale was again noted. The Panel requested its new chairman to submit a short note on this matter to some of the major journals in marine science. The Panel recommended strongly that all calibration certificates and similar documents should state the use of the new scale.

Thermal Expansion

A report was read from Dr. Ivanoff-Frantzkevich concerning Russian measurements of thermal expansion, to be completed by mid-1970. Dr. Fofonoff reported on the present work of Bradshaw and Schleicher (W.H.O.I.) for salinities of 30.5, 35.0 and 39.5% at pressures from 1 to 1000 bars.

Pressure Dependence of Conductivity

The Panel discussed the need for new independent measurements of this function. The number of in situ pressure-conductivity-temperature instruments is rapidly increasing. Apart from experiments underway at the Institute of Applied Physics, Kiel, Panel members were not aware of a laboratory engaged in conductivity-pressure measurements. Members agreed to investigate the status of plans for such measurements.

There is also an urgent demand for extension of the temperature correction values of relative conductivity below the range published in the International Oceanographic Tables. The low range, below 12°C, is of special interest since most in situ conductivity measurements are made at low temperatures. At present, it is impossible to convert conductivity measured at low temperatures into conductivity at 15°C, by use of the tables.

The problem with respect to in situ instruments can be seen in the following system of ratios, developed by Dr. Fofonoff. These instruments measure the ratio

$$\frac{\lambda(T, S, P)}{\lambda(15, 35, 0)}$$

where λ, T, S, P indicate electrical conductivity, temperature, salinity and pressure respectively. To convert these measurements to salinities, it is necessary to know the function

$$f(T, S, P) = \frac{\lambda(T, S, P)}{\lambda(15, 35, 0)}$$

This ratio can be separated into several ratios, as follows:

$$\frac{\lambda(T, S, P)}{\lambda(15, 35, 0)} = \frac{\lambda(T, S, P)}{\lambda(T, S, 0)} \cdot \frac{\lambda(T, S, 0)}{\lambda(15, S, 0)} \cdot \frac{\lambda(15, S, 0)}{\lambda(15, 35, 0)}$$

The last ratio is R_{15} which is tabulated in the International Oceanographic Tables, but measurements of the second ratio have not been made. To calculate salinities from the measured ratio and measured temperature and pressure, it is necessary to measure the ratio

$$\frac{\lambda(T, S, 0)}{\lambda(T, 35, 0)}$$

at temperatures below 12°C, or to measure the ratio

$$\frac{\lambda(T, S, 0)}{\lambda(15, S, 0)}$$

Sound Velocity

Professor Kroebel reported on measurements of sound velocity as a function of salinity, temperature, and pressure. A new instrument, capable of such measurements at a new level of precision, has been developed at his Institute. When the fundamental relationships are known, sound velocity could be used for the determination of, for example, pressure or density. After visiting the Institute and seeing the outstanding instrumentation and experimental arrangements for measuring these fundamental relationships, the Panel agreed to give Professor Kroebel all possible support.

Equation of State

Dr. Fisher reported on progress in establishing a satisfactory equation of state for sea water. A summary of this report is attached.

Influence of Ionic Composition

Dr. Kremling reported his investigations on the influences on conductivity of changes of ionic composition of sea water at lower salinities. Note was made of previous papers of Park and Grasshoff, especially on the effect of the state of the carbonate system on conductivity. The Panel agreed that such changes should not be neglected. Verification of the combined effects of sampling, storage and changes in ionic composition is needed. Laboratory experiments show clearly that the third decimal place of salinity is influenced, making doubtful the accuracy to this place of salinity from conductivity measurements. The difference between accuracy and precision should be clearly understood by all users of conductivity instruments. Accuracy can be checked by measuring density with the new densitometer referred to above. Only with such measurements can the third decimal place be assured.

To check how changes in the carbon dioxide system affect the routine determination of salinity, the Panel proposed that interested institutions make replicate determinations on a number of samples, of conductivity ratio, density, chlorinity and pH at a number of time intervals after collection of the sample.

New Tables

New sigma-t tables should be calculated as soon as independent checks have been made by Dr. Kremling. The tables and nomographs should be ready for submission to UNESCO by the end of 1970. Oxygen saturation tables should be ready by mid-1970. It was agreed that these tables should have the arguments cm^3/dm^3 , salinity and temperature. Intervals should be full units of salinity and 0.2° in temperature. To facilitate computation of tables in other units, such as ml (S, T, P) per kilogram of water or micromoles or microgram atoms per liter, appropriate coefficients and equations should be published in the preface to the tables.

The new determinations of specific gravity do not deviate significantly from values published in the Knudsen Hydrographic Tables to the second decimal place in chlorinity. Therefore, the Panel felt that the Knudsen values are sufficient for the computation of a salinity-chlorosity table at 20°C . Professor Grasshoff was asked to compile such a table with suitable arguments and intervals. This table should be included as an annex to the International Oceanographic Tables, as recommended at the Bern meeting of the Panel.

Business Matters

At the conclusion of the meeting, Professor Grasshoff was selected as the next Chairman.

It was agreed that the Panel should meet again when recommended investigations and measurements had been completed, and when further sections of the International Oceanographic Tables could be considered.

The two attached recommendations were formally adopted, and the Chairman was requested to bring them to the attention of the sponsoring bodies.

Gratitude was expressed to the various Panel members who had reported on work accomplished since the last meeting, and to Professor Kroebel for the hospitality of his Institute. The meeting closed at noon on 12 December.

Recommendation No. 1

The Joint Panel on Oceanographic Tables and Standards determined that knowledge of the absolute density of sea water as a function of temperature and salinity is necessary to an accuracy of one part per million. Such precision cannot be obtained without measurements of density of pure water to at least the same accuracy in order to use pure water as a reference for the sea water measurements. With the adoption of the new International Practical Temperature Scale in 1968 (Metrologia, 1969, V (2), pp. 35-44) in which the triple point of pure water is taken to be of water having the isotopic composition of ocean water, it is recommended that measurements of the following properties be made at a pressure of one normal atmosphere of degassed water of known isotopic composition, preferably as close as possible to that specified above.

- 1) Absolute density at 4°C and preferably at at least two other temperatures 0° and 20°C.
- 2) Thermal expansion to an accuracy sufficient to calculate density to the required accuracy from 0° to 40°.

The Panel recommends that the measurements be made at least at two different laboratories, such as Bureau International des Poids et Mesures, National Bureau of Standards, National Physical Laboratory.

Considering that, at temperatures superior to 16°C, the density of pure water is now known only with an insufficient precision, it is recommended that, at the time of future determinations of density of sea water, the calibration with pure water is made at 4 or 0°C solely, the thermic dilatation of the sinker (or pycnometer), if it is not known, being able to be determined on a sample of same material, interferometrically.

The Panel hopes that, if necessary, funds can be obtained to insure that this work can be accomplished.

Recommendation No. 2

Taking into account the increasing use of instruments for in situ measurements of conductivity, the Joint Panel strongly recommends that:

- a) High precision measurements of conductivity ratio of sea water are carried out in the temperature range 0°C to 14°C.
- b) That high precision measurements are made of conductivity as function of temperature and pressure.
- c) That high precision measurements are made of sound velocity as function of temperature, salinity, and pressure.

Analytic Equation of State for Water and Sea Water

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The following is a brief summary of the results of work reported at the meeting of the Joint Panel on Tables and Oceanographic Standards in Kiel, Germany, December, 1970. This work will be presented for publication in more detail at a later date, probably in the Journal of Geophysical Research.

The equation used is the Tumlirz equation used by Eckart ^{1/} in his paper on this subject

$$V = V_{\infty} + \frac{\lambda}{P_0 + P} \quad (1)$$

where V is the specific volume (cc/gm), P the pressure (bars) and V_{∞} , λ , and P_0 are temperature dependent parameters. This equation fits the pure water PV data of Kell and Whalley ^{2/} (K&W) to a precision with the standard deviation of approximately 10 PPM over the temperature range of 0 to 100°. A total of 20 terms appear in the three parameters V_{∞} , λ and P (Table I).

In attempting to fit Eq. (1) to the sea water data of Wilson and Bradley ^{3/}, (W&B), the most extensive set of experimental data from a single laboratory, we found that P_0 , λ and V_{∞} displayed an erratic

dependence on salinity. When P_0 was constrained to be the value derived from the pure water data of Kell and Whalley, it was found that P_0 and V_{∞} displayed a linear dependence on salinity. Finally, the equation used to fit the sea-water data is that shown in Equation (2)

$$V = V_{\infty} - K_1 S + \frac{\lambda}{P_0 + K_2 S + P} \quad (2)$$

where λ , V_{∞} and P_0 are those values used to fit the pure water data. K_1 displays a quadratic temperature dependence and K_2 a linear one (Table I).

Use of Bradshaw and Schleicher's ^{4/} (B&S) data on thermal expansion has been incorporated in our results in the coefficient K_1 . It appears from the B&S data that the W&B data is less reliable at low temperatures.

It should be noted that the pure water equation has a density maximum at 4.00°C. Use has been made of the atmospheric pressure data discussed by Kell ^{5/} in addition to the PV data of K&W.

The density maximum for sea water shows a greater salinity dependence; that is, the cross-over of the freezing point and the density maximum occurs at a lower salinity than stated in the text books, in this case at ~22‰ instead of ~25‰.

This equation, FWD for Fisher, Williams and Dial, then requires 20 terms for the 0-150° pure water data and only five additional terms for sea water. A truncated equation for pure water will be examined to see if the number of parameters for pure water can be reduced in order

to represent only the data between 0° and 40°.

Table II shows the fit of the FWD equation to the W&B data.

Table III summarizes results of various investigators for the thermal expansion coefficient of sea water shown in the W&B technical report along with our results.

Table IV in an analogous manner summarizes the specific volume results along with ours and those calculated by us from Li's results.

Similarly, Table V summarizes the compressibility results.

In Table VI we compare our results for thermal expansion ($\partial V/\partial T$) against those of B&S as a function of temperature, salinity and pressure. At 0° we find the greatest disagreement with their results.

In Table VII we do see, however, that changes in specific volumes from -2° to +2° calculated by the FWD equation compare very favorably with the results of B&S. In this case we are comparing our values from our equation against their raw data.

Values of the adiabatic gradient calculated from the FWD equation for S=35‰ were slightly lower than those reported by Fofonoff ^{6/}, for example, 4% at 2° and 400 bars and 7% at 2° and 1,000 bars.

REFERENCES

1. C. Eckart, Am. Jour. Sci., 256, 225 (1958).
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3. W. Wilson and D. Bradley, NOLTR 66-103, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland (1966).
4. A. Bardshaw and K.E. Schleicher, "Direct Measurement of Thermal Expansion of Sea Water under Pressure", submitted for publication to Deep Sea Research.
5. G.S. Kell, J. Chem. Engr. Data, 12, 66 (1967).
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TABLE I

TUMLIRZ EQUATION FOR PURE WATER AND SEA WATER

$$V = V_{\infty} - K_1 S + \frac{\lambda}{P_0 + K_2 S + P}$$

$$\lambda = 1788.316 + 21.55053 * T - 0.4695911 * T^2 + 3.096363 \times 10^{-3} T^3 - .7341182 \times 10^{-5} * T^4$$

$$P_0 = 5918.499 + 58.05267 * T - 1.1253317 * T^2 + 6.6123869 \times 10^{-3} * T^3 - 1.4661625 \times 10^{-5} * T^4$$

$$V_{\infty} = .6980547 - .7435626 * 10^{-3} * T + .3704258 \times 10^{-4} * T^2 - .6315724 \times 10^{-6} * T$$

$$+ .9829576 \times 10^{-8} * T^4 - .1197269 \times 10^{-9} * T^5 + .1005461 \times 10^{-11} * T^6$$

$$- .5437898 \times 10^{-14} * T^7 + .169946 \times 10^{-16} * T^8 - .2295063 \times 10^{-19} * T^9$$

$$K_1 = 2.679 \times 10^{-4} + 2.02 \times 10^{-6} * T - 6.0 \times 10^{-9} * T^2$$

$$K_2 = 10.874 - 4.1384 * 10^{-2} * T$$

λ bars cc/gm

P, P_0 bars

K_2 bar/o/oo

V_{∞} cc/gm

K_1 cc/gm/o/oo

TABLE II

Standard deviations in parts per million of the fit of the FWD equation to raw specific volume data of Wilson and Bradley vs. temperature and salinity. (Temperature cited is nominal since data were taken at varying temperatures near cited one.) The average of the standard deviations is 107 ppm for all the data.

| T ° | S o/oo | 10.221 | 20.720 | 30.881 | 35.568 | 40.370 |
|-------|--------|--------|--------|--------|--------|--------|
| ~ 0° | | 208 | 175 | 230 | 264 | 156 |
| ~ 5° | | 173 | 129 | 212 | 187 | 236 |
| ~ 10° | | 128 | 51 | 167 | 172 | 45 |
| ~ 15° | | 102 | 38 | 94 | 134 | 55 |
| ~ 20° | | 42 | 76 | 44 | 140 | 37 |
| ~ 25° | | 17 | 60 | 85 | 95 | 62 |
| ~ 30° | | 17 | 106 | 93 | 47 | 104 |
| ~ 35° | | 22 | 117 | 55 | 43 | 98 |
| ~ 40° | | 19 | 154 | 34 | 100 | 161 |

TABLE III

THERMAL EXPANSION OF SEA WATER (S = 35°/00)
COMPARISON TABLES

| T°C | P Bars | Hydrographic Tables x 10 ⁻⁵ | Eckart x 10 ⁻⁵ | Crease x 10 ⁻⁵ | NOL x 10 ⁻⁵ | FWD x 10 ⁻⁵ |
|-----|-----------|--|------------------------------|------------------------------|---------------------------|---------------------------|
| 0° | 1 | 5.2 | 8.0 | 5.6 | 7.8 | 5.76 |
| | 200 | 10.5 | 13.4 | 10.6 | 13.2 | 10.9 |
| | 400 | 15.4 | 18.2 | 15.0 | 18.0 | 15.4 |
| | 600 | 19.8 | 22.5 | 17.1 | 22.2 | 19.3 |
| | 800 | 23.2 | 26.6 | 22.6 | 26.1 | 22.6 |
| 10° | 1000 | 26.5 | 29.5 | 25.6 | 29.5 | 25.5 |
| | 1 | 16.7 | 16.2 | 16.7 | 16.3 | 16.6 |
| | 200 | 20.2 | 19.9 | 20.1 | 20.0 | 20.1 |
| | 400 | 23.3 | 23.1 | 23.2 | 23.3 | 23.2 |
| | 600 | 26.1 | 26.0 | 26.1 | 26.3 | 25.9 |
| 20° | 800 | 28.6 | 28.8 | 28.6 | 29.0 | 28.3 |
| | 1000 | 30.9 | 30.7 | 30.8 | 31.3 | 30.5 |
| | 1 | 25.7 | 23.8 | 25.7 | 24.1 | 25.6 |
| | 200 | 27.8 | 26.2 | 27.7 | 26.5 | 27.8 |
| | 400 | 29.8 | 28.2 | 29.7 | 28.6 | 29.7 |
| 30° | 600 | 31.7 | 30.0 | | 30.6 | 31.5 |
| | 800 | 33.5 | 31.7 | | 32.3 | 33.1 |
| | 1000 | 35.5 | 32.9 | | 33.8 | 34.6 |
| | 1 | 33.5 | 31.3 | 33.4 | 31.7 | 33.4 |
| | 200 | 34.7 | 32.5 | 34.6 | 33.0 | 34.5 |
| 40° | 400 | 36.1 | 33.6 | 35.7 | 34.2 | 35.6 |
| | 600 | 37.6 | 34.4 | | 35.2 | 36.5 |
| | 800 | 39.3 | 35.2 | | 36.1 | 37.5 |
| | 1000 | 41.4 | 35.8 | | 36.9 | 38.3 |
| | 1 | 41.0 | 39.4 | | 39.6 | 40.5 |
| 40° | 200 | 41.8 | 39.5 | | 40.0 | 40.7 |
| | 400 | 43.0 | 39.5 | | 40.2 | 41.1 |
| | 600 | 44.6 | 39.5 | | 40.5 | 41.4 |
| | 800 | 46.9 | 39.5 | | 40.6 | 41.7 |
| | 1000 | 49.6 | 39.5 | | 40.7 | 42.1 |

TABLE IV

SPECIFIC VOLUME OF SEA WATER, (S = 35°/00)
COMPARISON TABLES (cm³/gm)

| T°C | P Bars | Hydrographic Tables | Eckart | Crease | NOL | FWD |
|-----|-----------|------------------------|--------|--------|-------|-------|
| 0° | 1 | .9726 | .9726 | .9727 | .9726 | .9725 |
| | 200 | .9639 | .9640 | .9640 | .9638 | .9638 |
| | 400 | .9557 | .9557 | .9558 | .9556 | .9556 |
| | 600 | .9479 | .9480 | .9480 | .9479 | .9479 |
| | 800 | .9406 | .9407 | .9407 | .9406 | .9406 |
| 10° | 1000 | .9337 | .9338 | .9338 | .9337 | .9337 |
| | 1 | .9737 | .9736 | .9737 | .9738 | .9736 |
| | 200 | .9654 | .9654 | .9654 | .9654 | .9653 |
| | 400 | .9575 | .9575 | .9576 | .9576 | .9575 |
| | 600 | .9501 | .9502 | .9502 | .9502 | .9500 |
| 20° | 800 | .9430 | .9432 | .9432 | .9432 | .9430 |
| | 1000 | .9364 | .9366 | .9365 | .9366 | .9363 |
| | 1 | .9758 | .9757 | .9758 | .9757 | .9757 |
| | 200 | .9677 | .9678 | .9678 | .9677 | .9677 |
| | 400 | .9601 | .9601 | .9602 | .9601 | .9600 |
| 30° | 600 | .9528 | .9530 | .9529 | .9529 | .9528 |
| | 800 | .9460 | .9462 | .9461 | .9461 | .9459 |
| | 1000 | .9395 | .9397 | .9394 | .9396 | .9394 |
| | 1 | .9787 | .9784 | .9789 | .9784 | .9786 |
| | 200 | .9708 | .9706 | .9709 | .9706 | .9707 |
| 40° | 400 | .9632 | .9631 | .9632 | .9631 | .9632 |
| | 600 | .9561 | .9560 | .9560 | .9560 | .9560 |
| | 800 | .9494 | .9493 | .9491 | .9493 | .9492 |
| | 1000 | .9431 | .9430 | .9424 | .9429 | .9428 |
| | 1 | .9823 | .9819 | | .9819 | .9722 |
| 40° | 200 | .9745 | .9741 | | .9741 | .9744 |
| | 400 | .9760 | .9666 | | .9667 | .9669 |
| | 600 | .9601 | .9596 | | .9596 | .9598 |
| | 800 | .9535 | .9529 | | .9529 | .9530 |
| | 1000 | .9473 | .9466 | | .9466 | .9466 |

TABLE V

COMPRESSIBILITY OF SEA WATER, S = 35.00 (Bars⁻¹)
COMPARISON TABLES

| T°C | P Bars | Hydrographic Tables x 10 ⁻⁶ | Eckart x 10 ⁻⁶ | Crease x 10 ⁻⁶ | NOL x 10 ⁻⁶ | FWD x 10 ⁻⁶ |
|-----|-----------|--|------------------------------|------------------------------|---------------------------|---------------------------|
| 0° | 1 | 46.2 | 46.5 | 46.4 | 46.7 | 46.3 |
| | 200 | 44.0 | 44.0 | 44.0 | 44.1 | 43.9 |
| | 400 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 |
| | 600 | 39.7 | 39.5 | 39.6 | 39.5 | 39.6 |
| | 800 | 37.8 | 37.5 | 37.7 | 37.5 | 37.7 |
| | 1000 | 36.2 | 35.7 | 35.9 | 35.7 | 36.0 |
| 10° | 1 | 44.1 | 44.1 | 44.1 | 44.3 | 44.0 |
| | 200 | 42.0 | 41.8 | 41.9 | 42.0 | 41.9 |
| | 400 | 39.9 | 39.7 | 39.9 | 39.8 | 39.9 |
| | 600 | 38.0 | 37.8 | 38.1 | 37.8 | 38.1 |
| | 800 | 36.4 | 36.0 | 36.3 | 36.0 | 36.4 |
| | 1000 | 34.9 | 34.3 | 34.6 | 34.3 | 34.8 |
| 20° | 1 | 42.6 | 42.5 | 42.7 | 42.7 | 42.6 |
| | 200 | 40.6 | 40.5 | 40.6 | 40.5 | 40.6 |
| | 400 | 38.7 | 38.5 | 38.7 | 38.5 | 38.8 |
| | 600 | 36.9 | 36.7 | 36.7 | 36.7 | 37.0 |
| | 800 | 35.3 | 35.0 | 35.0 | 35.0 | 35.4 |
| | 1000 | 33.9 | 33.4 | 33.4 | 33.4 | 33.9 |
| 30° | 1 | 41.8 | 41.6 | 41.9 | 41.7 | 41.7 |
| | 200 | 39.8 | 39.6 | 39.8 | 39.7 | 39.8 |
| | 400 | 37.9 | 37.8 | 38.0 | 37.8 | 38.1 |
| | 600 | 36.1 | 36.1 | 36.0 | 36.0 | 36.4 |
| | 800 | 34.4 | 34.4 | 34.4 | 34.4 | 34.8 |
| | 1000 | 32.9 | 32.9 | 32.8 | 32.8 | 33.4 |
| 40° | 1 | 41.4 | 41.3 | 41.2 | 41.4 | 41.4 |
| | 200 | 39.3 | 39.3 | 39.3 | 39.3 | 39.5 |
| | 400 | 37.2 | 37.5 | 37.4 | 37.7 | 37.7 |
| | 600 | 35.3 | 35.8 | 35.7 | 36.1 | 36.1 |
| | 800 | 33.4 | 34.3 | 34.1 | 34.5 | 34.5 |
| | 1000 | 31.6 | 32.8 | 32.6 | 33.1 | 33.1 |

TABLE VI

Comparison of values of $\frac{\partial v^w}{\partial T}_{T,P,S}$ in parentheses calculated from FWD equation with those of Bradshaw and Schleicher computed from their comprehensive formula.

$$\text{Unit of } \frac{\partial v^w}{\partial T}_{T,P,S} = 10^{-6} \frac{\text{cm}^3}{\text{g}^\circ\text{C}}$$

S = 30.50°/oo

| T°C | 0 | | 10 | | 20 | | 30 | |
|---------|-------|-----|-------|-----|-------|-----|-------|-----|
| P, bars | | | | | | | | |
| 1 | (43) | 39 | (154) | 154 | (246) | 246 | (325) | 324 |
| 500 | (159) | 158 | (230) | 229 | (291) | 290 | (345) | 346 |
| 1000 | (235) | 240 | (284) | 284 | (324) | 323 | (362) | 362 |

S = 35.00°/oo

| T°C | 0 | | 10 | | 20 | | 30 | |
|---------|-------|-----|-------|-----|-------|-----|-------|-----|
| P, bars | | | | | | | | |
| 1 | (56) | 52 | (162) | 162 | (250) | 251 | (327) | 327 |
| 500 | (166) | 166 | (234) | 234 | (293) | 293 | (346) | 347 |
| 1000 | (238) | 244 | (285) | 286 | (325) | 325 | (361) | 363 |

S = 39.50°/oo

| T°C | 0 | | 10 | | 20 | | 30 | |
|---------|-------|-----|-------|-----|-------|-----|-------|-----|
| P, bars | | | | | | | | |
| 1 | (68) | 65 | (169) | 170 | (254) | 256 | (329) | 329 |
| 500 | (172) | 174 | (238) | 239 | (295) | 296 | (347) | 348 |
| 1000 | (241) | 248 | (287) | 289 | (325) | 326 | (361) | 363 |

TABLE VII

Calculated values from FWD equation vs. B&S observed values for the change in the specific volume of sea water from -2° to $+2^{\circ}$. FWD values are listed in parentheses: Units are in 10^{-6} cc/gm.

| | | | | | |
|---------------|-----------------|------------------|------------------|------------------|------------------|
| P bars | 201.3 | 401.2 | 601.0 | 800.9 | 1000.8 |
| Salinity o/oo | 35.004 | 35.005 | 35.004 | 35.002 | 35.006 |
| T°C | | | | | |
| -2 | | (-269) -277.1 | (-352) -356.9 | (-415) -424.3 | (-467) -480.5 |
| -1 | (-101) -97.5 | | | | |
| 0 | (0) 0 | (0) 0 | (0) 0 | (0) 0 | (0) 0 |
| +2 | (230) 225 | (310) 310 | (379) 383 | (437) 445 | (486) 498 |