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CONCEPT EVALUATION FOR NEW SMALL SCALE OCEANOGRAPHIC TEMPERATUR--ETC(U)
AUG 80 J P DUGAN
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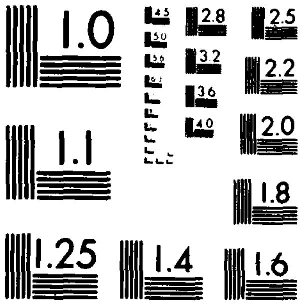

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A new concept for making measurements of ocean temperature and salinity down to spatial scales of about one centimeter is evaluated. A common measurement cell incorporating both an accurate electrical conductivity sensor and a sound velocity sensor is expected to provide fast response rates and little bias due to "mismatch" between the sensor response rates. Resolution and frequency response are limited only by cell size and flushing rate.

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CONTENTS

CONCEPT EVALUATION FOR NEW SMALL SCALE OCEANOGRAPHIC TEMPERATURE AND SALINITY MEASUREMENT TECHNIQUE

INTRODUCTION

The dissipation scale of temperature fluctuations in the ocean is the order of one centimeter. Measurements on this scale are made in order to estimate the rate of local energy dissipation. The measurement techniques presently utilized almost entirely involve research instrumentation which is of a slow, free-falling nature (1-3). The reason for the slow fall rate of this instrumentation is to provide sufficient time for a thermistor to respond to the temperature fluctuations on this scale. The reason for the free-falling mode of operation is to decouple the instrument platform from ship motion and thus avoid contamination of the data.

The purpose of this note is to describe a proposed instrument system which could be deployed at much higher speed and, hopefully, mounted on a towed or or lowered platform. This instrument would obtain the required temperature information (and, incidentally, salinity information) by measuring the electrical conductivity and the sound velocity. The advantage of these two measurements is that each is dependent only upon the geometry of the sensor cell and its flushing rate; a fast flushing rate yields a fast response time. Both sensors could be mounted in the same cell, and a "mismatch" in the response times of the two sensors substantially could be avoided.

In the following sections, estimates of the resolution and accuracy of a device acting on this principle are calculated using known resolution and accuracies of sound velocity and electrical conductivity sensors which presently are available for measurements at sea. No attempt is made to review common errors in the precision or accuracy of these sensors. Lovett (4), Mackenzie (5), and Fofonoff et al. (6), are just a few of many references which explore these errors in the individual sensors.

Manuscript submitted April 15, 1980.

SENSOR FREQUENCY RESPONSE

Errors in quantities calculated from oceanographic measurements often occur when one sensor responds at a faster rate to fluctuations than does another one. A case in point is the error in salinity calculations commonly called salinity "spiking" (7-9). This error occurs because the sensor which measures electrical conductivity responds much faster to fluctuations than does the nearby temperature sensor (thermistor). Conductivity is a strong function of temperature as well as salinity and, thus, the system obtains two different estimates of temperature during fast transients. This error can be minimized by appropriate corrections (7-9) but the corrections are critically dependent upon accurate estimates of response rates. These estimates in turn depend upon sensor orientation and speed through the water and these seldom are constant in towed or lowered instruments.

A second disadvantage in using correction procedures for temperature response mismatch is that both salinity and temperature data ultimately are degraded to the spatial (or temporal) scales resolved by the temperature sensor. The thermistors commonly used in oceanographic sensors have to be rugged to withstand the environment, so they respond rather slowly. Their response begins to roll off at frequencies around 5-20 hertz (10).

On the other hand, the conductivity cell responds very quickly to fluctuations. Its response is limited only by the rate at which water passes through the cell. If the boundary layers are kept small in relation to the total volume of the measurement section, this rate can approach 10^3 hertz.

Similarly, a sing-around cell for measuring sound speed can respond at very high rates. In this case, the flushing rate again is no problem, but there is a minor restriction on sample rates due to the finite (but small) time it takes for an acoustic pulse to travel across the cell and back. This time is about 70 μsec for state-of-the-art instruments, so kilohertz rates again are realizable.

For a cell size the order of one centimeter and for a tow or lowering speed of 1-5 m/sec, the water ideally is fully flushing from the cell at a rate of 100-500 times per second. This would be the limiting rate at which independent samples are available to the sensors, so the response of the instrument would begin to roll off at frequencies higher than this. However, since the sensors can respond considerably faster than this rate, an even higher sampling rate might be useful to beat down any sources of electronic or sampling noise. There is no reason to expect "mismatch" between the sensors unless the spatial geometry sampled by one is not the same as that sampled by the other. This is of some concern since the sound velocity sensor integrates along the line of flight of the acoustic pulse and the conductivity sensor integrates over a potential field in the vicinity of the contacts. The effect on performance of any mismatch of this origin could be measured and/or modelled. It is not our purpose to do this at this state, but only to point out a potential source of measurement degradation on the very fine scale.

TEMPERATURE AND SALINITY ESTIMATES

Since a proposal to use sound velocity and electrical conductivity measurements to estimate water temperature and salinity is unique, it is important to calculate just how accurately these variables can be estimated. In particular, given state-of-the-art error estimates of conductivity, sound velocity, and pressure, what are the corresponding error estimates in the derived parameters?

Standard tables and/or empirical formulae which previously have been fitted to tabular data will be used for each of the variables. The formulae generally are backwards for our purpose; ie, Wilson's or Del Grosso's equations (11,12) give sound velocity in terms of temperature, salinity, and pressure. In the vicinity of any point in the parameter space, these relations can be represented to first order by

$$sv = \alpha T + \beta S + \epsilon p \tag{1}$$

$$C = \gamma T + \delta S + \nu p \tag{2}$$

where

$$\begin{array}{rcl}
2.15 & \leqslant \alpha \leqslant & 4.6 & [\mathrm{m/s/^\circ C}] \\
1.29 & \leqslant \beta \leqslant & 1.41 & [\mathrm{m/s/‰}] \\
.72 & \leqslant \gamma \leqslant & 1.20 & [\mathrm{mmho/cm/^\circ C}] \\
.72 & \leqslant \delta \leqslant & 1.64 & [\mathrm{mmho/cm/‰}] \\
.017 & \leqslant \epsilon \leqslant & .019 & [\mathrm{m/s/dbar}] \\
.0004 & \leqslant \nu \leqslant & .0015 & [\mathrm{mmho/cm/dbar}]
\end{array} \tag{3}$$

in the range 0-30°C and 32-36 $^{\circ}/_{\circ\circ}$. In equation 1 and 2, sv is sound velocity, C is electrical conductivity, T is temperature, S is salinity, and p is pressure. The units are given in the brackets in expressions 3. The range of α, β, and ϵ were obtained from Wilson's equations (11), those of γ and δ from Reeburgh (13), and of ν from Bradshaw and Schleicher (14).

Inverting the equations 1 and 2, the temperature and salinity are given by

$$T = (\alpha\delta - \gamma\beta)^{-1}[\delta sv - \beta C + (\nu\beta - \epsilon\delta)p] \tag{4}$$

$$S = (\alpha\delta - \gamma\beta)^{-1}[-\delta sv + \alpha C + (\epsilon\gamma - \alpha\nu)p]. \tag{5}$$

The constants involving the Greek letters give the sensitivity of temperature and salinity on the measured variables sound velocity, conductivity, and pressure. In the following, the dependence upon pressure is suppressed. The terms involving the pressure in equations 4 and 5 are not negligible in the absolute accuracy of calculations for temperature and salinity, but they pose no issue because of the smallness of the constants ϵ and ν, and the high accuracy with which pressure can be measured.

It is useful to plot the values of the coefficients in equations 4 and 5. These coefficients provide the transfer functions for uncertainties in the measured values of sound velocity and electrical conductivity into uncertainties in the calculated salinity and temperature. Figures 1 and 2 are contour plots of the values of these sensitivity coefficients for the uncertainty in conductivity. The figures are used in the following way. For any given temperature and salinity, the value indicated in each figure is the multiplying number for uncertainty in the calculated value (temperature or salinity) per unit uncertainty in the measured variable (electrical conductivity). The plots were obtained from the data in Reeburgh (13), and the abscissa and ordinate were chosen to be temperature and salinity rather than the measured values only for historical reasons. The corresponding transfer coefficients for uncertainty in the calculated value of temperature and salinity per unit uncertainty in sound velocity are given in Figures 3 and 4. These plots were determined by a simple fit to gradients of Wilson's equations (11).

Now, reasonable resolutions of oceanographic instrumentation for variables which are measured in situ are:

$$\begin{aligned} sv &\sim 1 \text{ cm/sec} \\ C &\sim .001 \text{ mmho/cm} \\ p &\sim .01 \text{ dbar} \end{aligned} \qquad (6)$$

These estimates do not represent any particular system in existence at the moment, but rather a combination of those with which NRL has some familiarity. The conductivity noise level is that of a Neil Brown CTD (Neil Brown Instrument Systems, 15, and Fofonoff et al., 6) and that of sound velocity represents specifications of Grundy (16) and InterOcean (17).

Using these values of resolution in conductivity and sound velocity with nominal values of the sensitivity coefficients yields the resolution in temperature and salinity. The pressure term is negligible and the remaining terms are the order:

$$\begin{array}{lcc} & \underline{\Delta C} & \underline{\Delta sv} \\ \text{T(°C)} & .001 & .003 \\ \text{S (‰)} & .001 & .008 \end{array} \qquad (7)$$

It is clear that the resolution of the sound velocity sensor, through its effect on the resolution in temperature, is the limiting factor. The resolution of 1 cm/sec for the sound velocity sensor has never really been pushed; it is entirely possible that a requirement of the type envisioned here could improve this by an order of magnitude. In the meantime, although this resolution is unacceptable for a microscale instrument, it remains useful for high speed acquisition of data on the fine scale down to lengths less than 50 cm. Figure 5 shows a temperature spectrum acquired by a horizontal tow of a thermistor in the seasonal thermocline of the ocean. The thermistor system had a noise level of about lm°C, and the spectrum for frequencies greater than 10 hz (length scales less than 50 cm) is white. A noise level of 3m°C corresponds to several meter wavelengths which confirms the usefulness of the present scheme down to this scale. However, if the temperature spectrum is simply extrapolated down to 1 cm, it appears that the required resolution is the order of 0.lm°C. Energetic dissipative patches in the ocean might be resolved by the present design, but the accurate representation of the average spectral level would require an order of magnitude improvement in the resolution of the sound velocity sensor and a concomitant improvement in the conductivity sensor.

The accuracy of this instrumentation is a function of the accuracies of the individual sensors. Reasonable accuracies of the oceanographic instrumentation for variables which are measured in situ are:

$$\begin{aligned} sv &\sim 10 \text{ cm/sec} \\ C &\sim .01 \text{ mmho/cm} \end{aligned} \tag{8}$$

so that the accuracies in the derived temperature and salinity values are the order:

$$\begin{array}{lcc} & \underline{\Delta C} & \underline{\Delta sv} \\ T(^\circ C) & .01 & .03 \\ S(‰) & .01 & .08 \end{array} \tag{9}$$

These values are significantly less than those available in the present direct measurement methods, and it would appear that this indirect measurement gains frequency response at some loss in overall accuracy. This circumstance could be at least partially overcome by combining high and low frequency temperature estimates in the way that the Neil Brown CTD circuitry presently combines thermistor and platinum resistor thermometer measurements.

Figures 1-4 are useful for exhibiting the range of variability of the transfer coefficients and, as used in the preceding paragraphs, for computing resolution and accuracy estimates for this instrument. However, in order to use the measured data to calculate values for temperature and salinity, it is necessary to have an explicit relationship for the derived quantities. The formulae of Wilson (11) and Perkin and Walker (18) have been used to generate a table of all the variables, and this table has been utilized to generate the explicit dependence illustrated in Figures 6 and 7. In practice, it is not clear whether a regression analysis which would yield an explicit functional dependence or a table look up procedure would be the more efficient in usage of computer time for calculations at high data rates. Nevertheless, the figures show the form of this dependence. Figure 6 illustrates lines of constant temperature and salinity as functions of conductivity and sound velocity. This figure represents conditions at the ocean surface, and Figure 7 represents conditions at the depth corresponding to 1000 dbar pressure. Each figure shows that the intersections of the families of isotherms and isohalines are reasonably nonparallel over the whole range of oceanographic conditions. Also, intercomparison of the figures shows that the effect of pressure to a good approximation only offsets the sound velocity axis, at least in the case of the upper ocean.

CONCLUSION

The rapid measurement of small scale temperature and salinity fluctuations in the ocean by the indirect means of measuring the electrical conductivity and sound velocity is feasible, given present technology in these sensors. Because of the rapid response of these sensors, it appears that spatial scales can be fully resolved to ten centimeters or less by instruments being lowered or towed at speeds up to 5m/s. However, correct spectral levels of scales smaller than order 50 cm would not be preserved unless there are significant improvements in the amplitude response (ie, significant decreases in noise level) of presently available sound velocity and electrical conductivity sensors. Also, this increase in frequency response is obtained at some loss in overall accuracy compared with a direct measurement of temperature.

It is recommended that a proof-of-principle test be conducted. Such a test could be accomplished with an experiment utilizing current technology. Data from a lowered instrument in a stratified laboratory tank or at sea which incorporates the required sensors in close proximity in the horizontal plane should be sufficient to test the principle. Important elements of such a test include estimates of the achieved sensor frequency response and estimates of mismatch between the sensors due to differences in spatial sampling. If such a test were successful, further development by integrating both sensors into a common cell and improving their sensitivity would be warranted.

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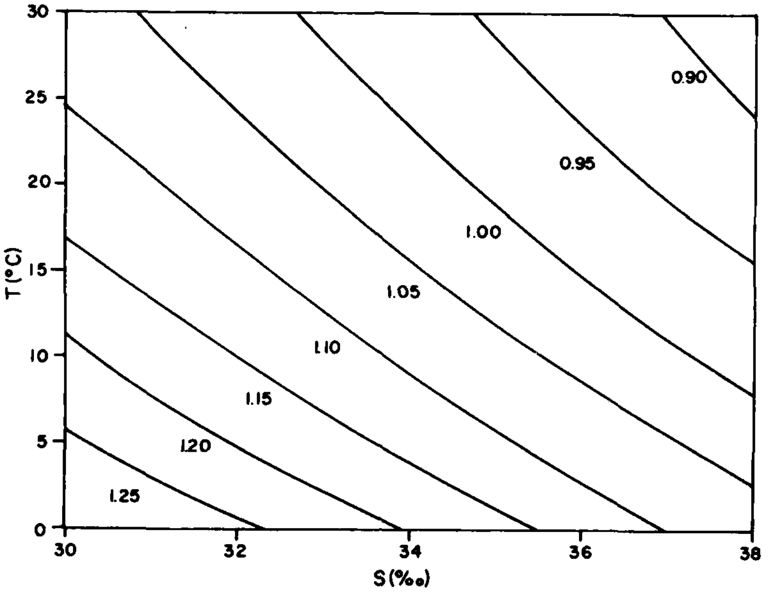

Fig. 1 — Sensitivity coefficient for temperature dependence on electrical conductivity (°C/mmho/cm)

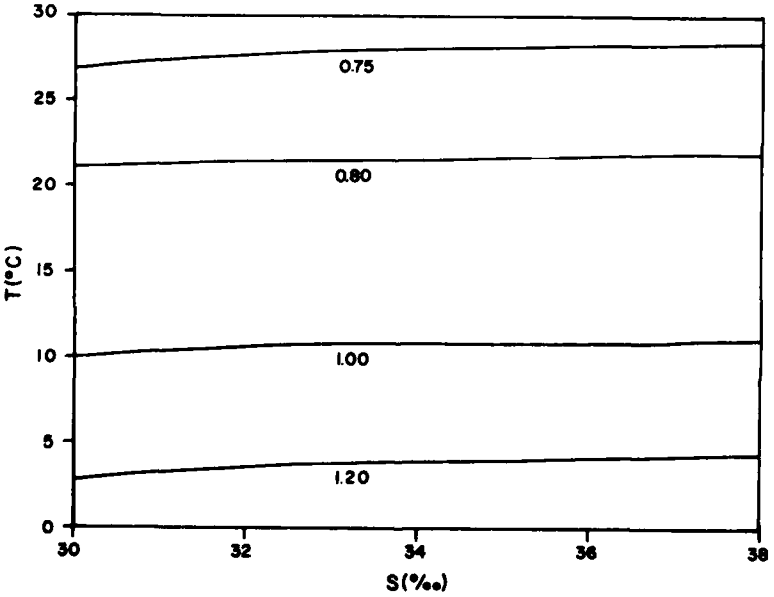

Fig. 2 — Sensitivity coefficient for salinity dependence on electrical conductivity (‰/mmho/cm)

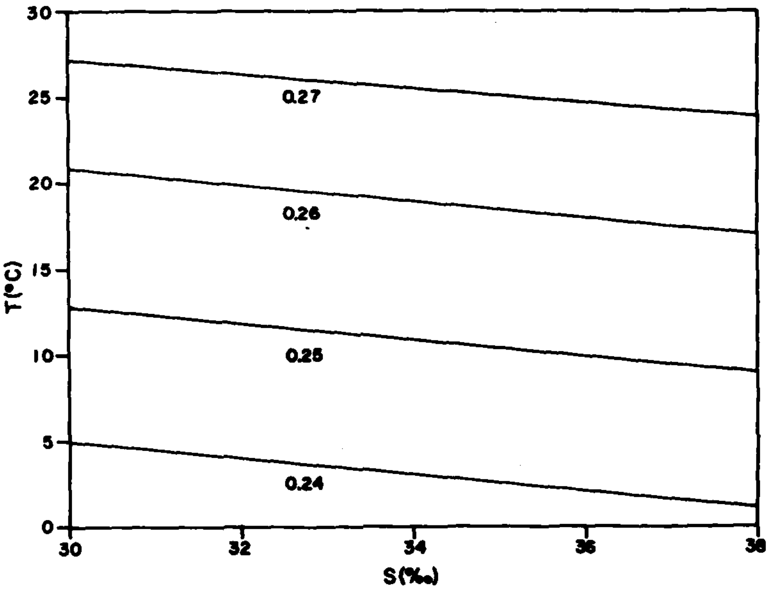

Fig. 3 — Sensitivity coefficient for temperature dependence on sound velocity (°C/m/s)

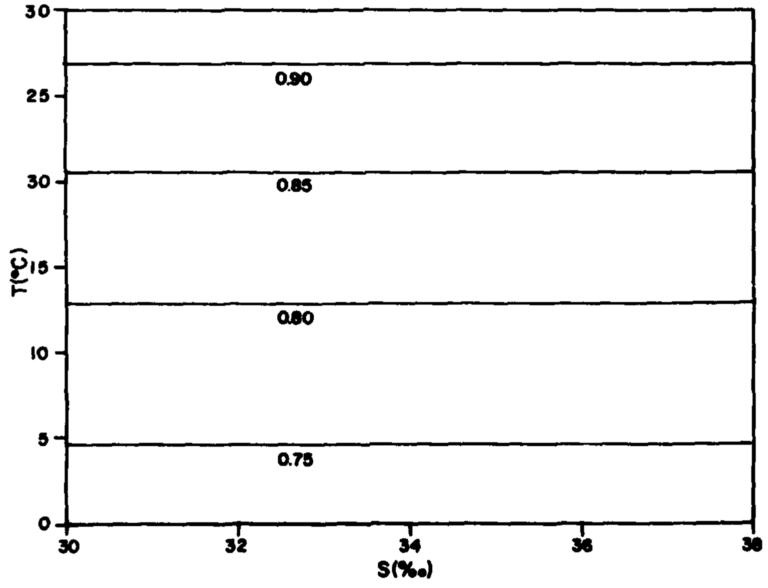

Fig. 4 — Sensitivity coefficient for salinity dependence on sound velocity (‰/m/s)

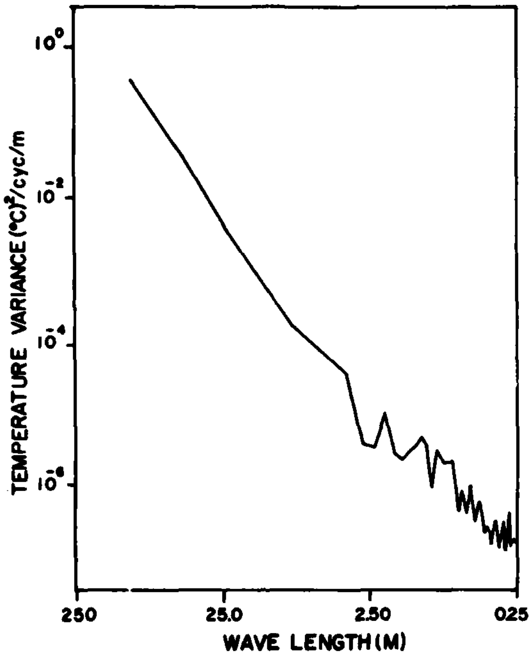

Fig. 5 — Horizontal temperature spectrum in seasonal thermocline acquired with thermistor tow

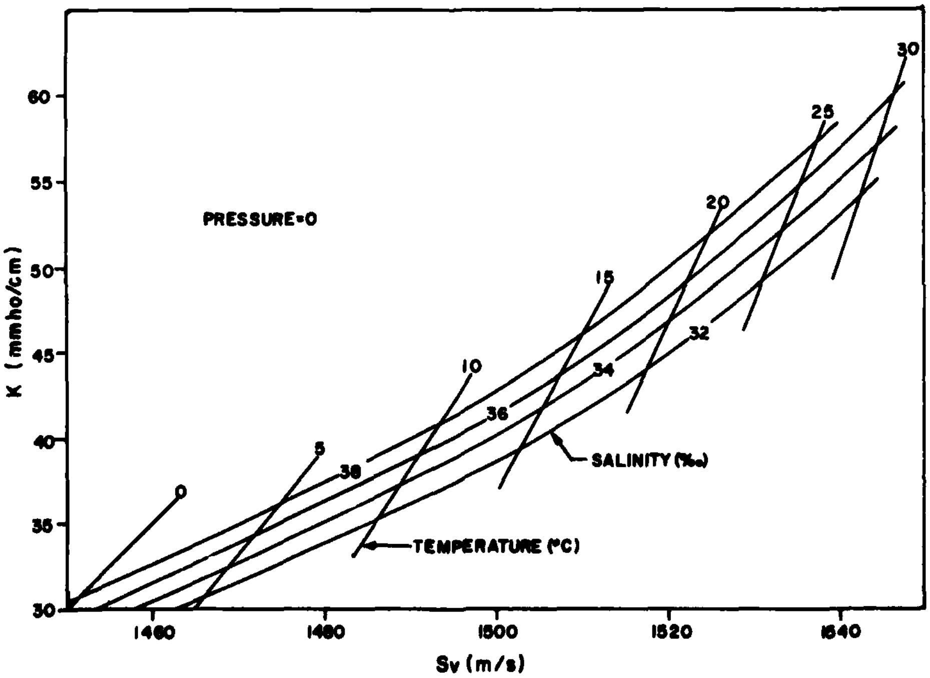

Fig. 6 — Temperature and salinity dependence on electrical conductivity and sound velocity at ocean surface

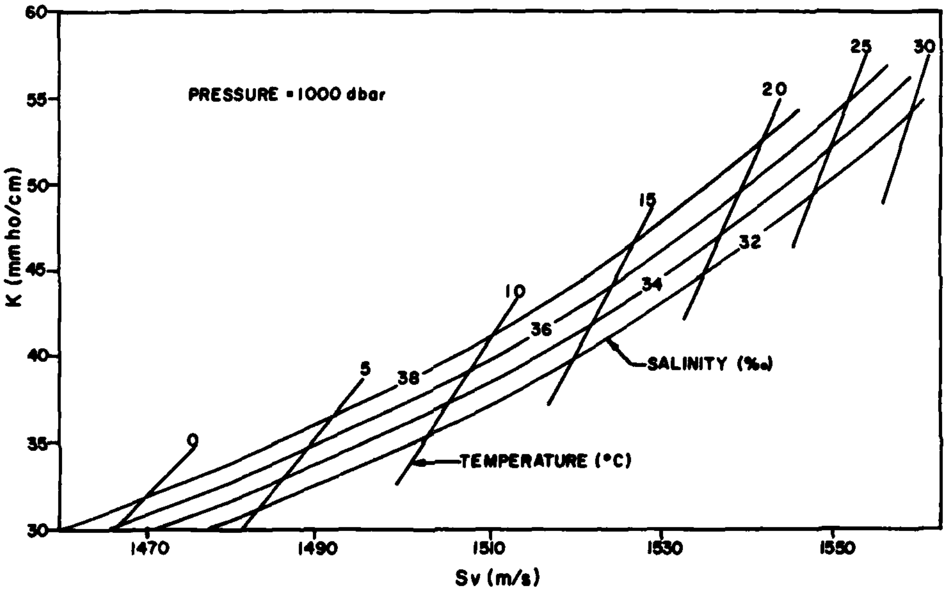

Fig. 7 — Temperature and salinity dependence on electrical conductivity and sound velocity at 1000 dbar pressure

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