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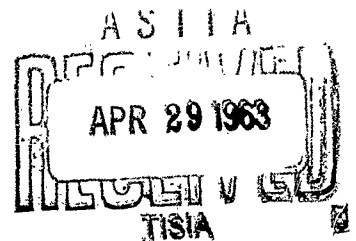
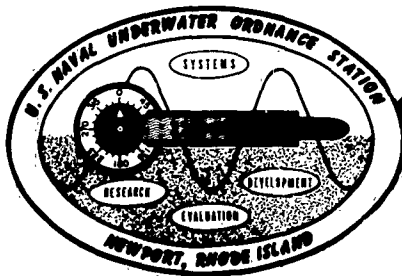
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INTERPRETING PROFILES OF
SOUND VELOCITY IN SEA WATER



**U.S. NAVAL
UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND**

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U. S. NAVAL UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND

TECHNICAL MEMORANDUM

INTERPRETING PROFILES OF
SOUND VELOCITY IN SEA WATER

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WEPTASK Assignment No.
RUTO-3E-000/219 1/SF-099-03-02 and
RU22-2E-000/219 1/R004-03-01

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FOREWORD

In evaluating any marine system (ASW, tracking, etc.), it is desirable to correlate system performance with environmental conditions. Sound velocity is often the only oceanographic parameter monitored during system tests. This report describes a technique for determining gross distributions of temperature and salinity from sound velocity profiles. This work was accomplished under Bureau of Naval Weapons WEPTASK Assignment No. RUTO-3E-000/219 1/SF-099-03-02 and RU22-2E-000/219 1/RO04-03-01.

SUMMARY

This report presents a technique^{is given} for the interpretation of sound velocity profiles in terms of basic oceanographic parameters of temperature, salinity and depth. An empirical relationship between these parameters and the speed of sound in sea water has been developed by Wayne D. Wilson of the U. S. Naval Ordnance Laboratory. Using Wilson's equation as a tool, graphs have been prepared which show the rate of change of sound velocity with respect to temperature, salinity, pressure, or any combination of these parameters. Typical sound velocity profiles are also presented and interpreted in terms of the environmental conditions which produce them. These graphs and analyses should help engineers to infer general oceanographic conditions from given sound velocity profiles, and to determine the strength and extent of temperature and salinity gradients.

ILLUSTRATIONS

Figure

1. Rate of Change of Sound Velocity with Respect to Temperature
2. Rate of Change of Sound Velocity with Respect to Temperature:
Salinity Correction
3. Rate of Change of Sound Velocity with Respect to Salinity
4. Rate of Change of Sound Velocity with Respect to Pressure
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Salinity Correction
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INTRODUCTION

Sound velocity is not the only oceanographic parameter which affects the performance of marine systems. Temperature and salinity distributions are often as useful and sometimes more important. But, after completing a series of acoustic tests in which only sound velocities were taken, test engineers often discover that it would be useful to have some idea of the gross distributions of temperature and salinity as well. This report presents a technique for inferring the gross distributions of temperature and salinity from sound velocity data and from a general knowledge of oceanographic distributions.

Wayne D. Wilson of the U. S. Naval Ordnance Laboratory has developed an equation which relates temperature, salinity and pressure of a sea water sample with the speed of sound propagation through the sample. A full explanation of Wilson's equation in terms of basic physical relationships and experimental results is contained in NAVORD Report No. 6986 (see bibliography). For purposes of this report Wilson's equation serves as a tool in constructing graphs which can be used by engineers to calculate variations in sound velocity with temperature, salinity and pressure, and to explain typical vertical sound velocity profiles in terms of temperature and salinity depth distribution.

SOUND VELOCITY IN SEA WATER

Wilson's equation for the speed of sound propagation in sea water is:

$$V = 1449.14 + \Delta V_T + \Delta V_P + \Delta V_S + \Delta V_{STP}.$$

$$\Delta V_T = C_1T + C_2T^2 + C_3T^3 + C_4T^4.$$

$$\Delta V_P = C_5P + C_6P^2 + C_7P^3 + C_8P^4.$$

$$\Delta V_S = C_9(S-35) + C_{10}(S-35)^2.$$

$$\Delta V_{STP} = (S-35)[C_{11}T + C_{12}T^2 + C_{13}P + C_{14}P^2 + C_{15}PT + C_{16}PT^2] \\ + P[C_{17}T + C_{18}T^2 + C_{19}T^3] + P^2[C_{20}T + C_{21}T^2] + C_{22}TP^3.$$

In this equation: V = velocity of sound in meters per second
 T = temperature in degrees centigrade
 S = salinity in grams per kilogram of sea water
 P = pressure in kilograms per square centimeter

and:

$C_1 = 4.5721$	$C_{12} = 7.7711 \times 10^{-7}$
$C_2 = -4.4531 \times 10^{-2}$	$C_{13} = 7.7016 \times 10^{-5}$
$C_3 = -2.6045 \times 10^{-4}$	$C_{14} = 1.2943 \times 10^{-7}$
$C_4 = 7.9851 \times 10^{-6}$	$C_{15} = 3.1580 \times 10^{-8}$
$C_5 = 1.60272 \times 10^{-1}$	$C_{16} = 1.5790 \times 10^{-9}$
$C_6 = 1.0268 \times 10^{-5}$	$C_{17} = -1.8607 \times 10^{-4}$
$C_7 = 3.5216 \times 10^{-9}$	$C_{18} = 7.4812 \times 10^{-6}$
$C_8 = -3.3606 \times 10^{-12}$	$C_{19} = 4.5283 \times 10^{-8}$
$C_9 = 1.39799$	$C_{20} = -2.5294 \times 10^{-7}$
$C_{10} = 1.6920 \times 10^{-3}$	$C_{21} = 1.8563 \times 10^{-9}$
$C_{11} = -1.1244 \times 10^{-2}$	$C_{22} = -1.9646 \times 10^{-10}$

The speed of sound propagation in sea water is shown to vary with temperature, salinity, pressure and a combination of all three. To determine these variations, the first step is to obtain the partial derivatives of the velocity equation with respect to temperature, salinity and pressure.

$$\begin{aligned} \frac{\partial V}{\partial T} = & C_1 + 2C_2T + 3C_3T^2 + 4C_4T^3 + C_{11}(S-35) + 2C_{12}(S-35)T \\ & + C_{15}(S-35)P + 2C_{16}(S-35)PT + C_{17}P + 2C_{18}PT + 3C_{19}PT^2 \\ & + C_{20}P^2 + 2C_{21}P^2T + C_{22}P^3. \end{aligned}$$

$$\begin{aligned} \frac{\partial V}{\partial S} = & C_9 + 2C_{10}(S-35) + C_{11}T + C_{12}T^2 + C_{13}P + C_{14}P^2 \\ & + C_{15}PT + C_{16}PT^2. \end{aligned}$$

$$\begin{aligned} \frac{\partial V}{\partial P} = & C_5 + 2C_6P + 3C_7P^2 + 4C_8P^3 + C_{13}(S-35) + 2C_{14}(S-35)P \\ & + C_{15}(S-35)T + C_{16}(S-35)T^2 + C_{17}T + C_{18}T^2 + C_{19}T^3 + 2C_{20}PT \\ & + 2C_{21}PT^2 + 3C_{22}P^2T. \end{aligned}$$

From these partial derivatives it is evident that the variations of velocity with temperature, salinity and pressure are themselves functions of the temperature, salinity and pressure. As there is no convenient way in which to present the variation of a quantity with respect to three variables, the variation of each partial derivative with respect to salinity was investigated. (This variation is represented as the partial derivative with respect to salinity of the temperature, salinity and pressure partial derivatives already obtained.) The resulting equations are:

$$\frac{\partial \left(\frac{\partial V}{\partial T} \right)}{\partial S} = C_{11} + 2C_{12}T + C_{15}P + 2C_{16}PT.$$

$$\frac{\partial \left(\frac{\partial V}{\partial S} \right)}{\partial S} = 2C_{10}.$$

$$\frac{\partial \left(\frac{\partial V}{\partial P} \right)}{\partial S} = C_{13} + 2C_{14}P + C_{15}T + C_{16}T^2.$$

These equations indicate that the rate of change with respect to salinity of the rates of change of sound velocity (with respect to temperature, salinity and pressure) is a function of temperature and pressure only. Using this relationship, the rate of change of sound velocity with respect to temperature (which, as already noted, is a function of temperature, salinity and pressure) may be expressed as a function of temperature, pressure and a constant reference salinity (S_0) plus the difference between the actual salinity and the reference salinity multiplied by the rate of change with respect to salinity of the rate of change of sound velocity with respect to temperature. The same procedure may be used to express the rate of change of sound velocity with respect to salinity or pressure. The three equations thus obtained are:

$$\frac{\partial V}{\partial T} = f_1(T, S, P) = f_1(T, S_0, P) + (S - S_0) \frac{\partial \left(\frac{\partial V}{\partial T} \right)}{\partial S}.$$

$$\frac{\partial V}{\partial S} = f_2(T, S, P) = f_2(T, S_0, P) + (S - S_0) \frac{\partial \left(\frac{\partial V}{\partial S} \right)}{\partial S}.$$

$$\frac{\partial V}{\partial P} = f_3(T, S, P) = f_3(T, S_0, P) + (S - S_0) \frac{\partial \left(\frac{\partial V}{\partial P} \right)}{\partial S}.$$

These substitutions are justified over the entire range of salinity because the rates of change of sound velocity with respect to temperature, salinity and pressure are all linear in salinity. The reference salinity selected was 35 grams per kilogram of sea water - a common salinity in the world's oceans.

VARIATION WITH TEMPERATURE, SALINITY AND PRESSURE.

Figures 1 through 6 illustrate graphically the general characteristics of variations in sound velocity with respect to temperature, salinity and pressure, and the interaction of these parameters. Figure 1 shows the rate of change of sound velocity with respect to temperature ($\partial V / \partial T$) as a function of temperature and pressure (salinity constant at 35 o/oo). It is

evident that temperature has a far greater influence than pressure on $\partial V/\partial T$. Moreover, the effect of temperature is inverse; $\partial V/\partial T$ decreases with increasing temperature. The effect of pressure on $\partial V/\partial T$ appears to depend on the temperature. At 0°C $\partial V/\partial T$ decreases with increasing pressure, whereas at 30°C $\partial V/\partial T$ increases with increasing pressure. The effect of salinity on $\partial V/\partial T$ is shown in figure 2 as a function of temperature and pressure. $\partial(\partial V/\partial T)/\partial S$ varies inversely with both temperature and pressure, the effect of pressure being greater at higher temperatures.

Figure 3 shows the rate of change of sound velocity with respect to salinity ($\partial V/\partial S$) as a function of temperature and pressure (salinity again constant at 35.6/00). $\partial V/\partial S$ varies inversely with temperature. With respect to pressure $\partial V/\partial S$ is almost constant, although there is an indication that it builds to a maximum with increasing pressure and then decreases as pressure continues to increase. The pressure at which this maximum occurs appears to vary slightly with temperature. With respect to salinity $\partial V/\partial S$ increases linearly at the rate of 3.384×10^{-3} meters/second per gram/kilogram per gram/kilogram of salinity.

Figure 4 shows the rate of change of sound velocity with respect to pressure ($\partial V/\partial P$) as a function of temperature and pressure (salinity again constant at 35.6/00). It is very difficult to describe the variations shown in this figure; therefore, the same material is presented in another form in figure 5. In this form $\partial V/\partial P$ increases with increasing pressure for temperatures less than 20°C . The rate of increase, however, decreases with increasing temperature. For temperatures above 20°C and pressures greater than 200 kilograms per square centimeter, the lines of constant $\partial V/\partial P$ reverse their curvature and become concave upward. No explanation of this will be offered because the purpose of this report is to explain the environment, not the physics behind Wilson's equation. Also, this area ($>20^{\circ}\text{C}$ and 100 kgm/cm^2) is outside the limits of natural variability in the world's oceans. The effect of salinity on $\partial V/\partial P$, shown in figure 6 as a function of temperature and pressure, is very small.

From these graphs (figures 1 through 6) the rate of change of sound velocity with respect to temperature, salinity, or pressure may be obtained (as follows) for any combination of temperature, salinity and pressure observed in the ocean to a depth of 5000 meters.

1. Locate the graph showing the rate of change of sound velocity with respect to the desired parameter (figure 1, 3, 4 or 5).
2. Locate the corresponding graph for salinity corrections (figure 2 or 6). The salinity correction to the rate of change of sound velocity with respect to salinity ($\partial V/\partial S$) is equal to 3.384×10^{-3} meters/second per gram/kilogram of salinity per gram/kilogram of salinity at all temperatures and salinity.

3. Read the value for rate of change of sound velocity at the desired temperature and pressure from the graph selected in step 1.
4. Determine the salinity correction factor at the desired temperature and salinity from the graph selected in step 2.
5. Subtract the reference salinity (35 o/oo) from the desired salinity and multiply this difference by the salinity correction factor determined in step 4.
6. Add the salinity correction determined in step 5 to the value for rate of change of sound velocity obtained in step 3.

INTERPRETING SOUND VELOCITY PROFILES

Standard vertical sound velocity profiles express sound velocity as a function of depth. The rate of change of sound velocity with respect to depth ($\partial V / \partial z$) may be considered as the sum of the rates of change of sound velocity with respect to temperature, salinity and pressure, each multiplied by the rate of change of the same parameter with respect to depth.

$$\frac{\partial V}{\partial z} = \left(\frac{\partial V}{\partial T} \right) \left(\frac{\partial T}{\partial z} \right) + \left(\frac{\partial V}{\partial S} \right) \left(\frac{\partial S}{\partial z} \right) + \left(\frac{\partial V}{\partial P} \right) \left(\frac{\partial P}{\partial z} \right).$$

The partial derivative notation has been used to indicate that temperature, salinity, pressure and sound velocity may vary in time or space at constant depth.

In considering sound velocity profiles it should be noted that $\partial T / \partial z$ and $\partial S / \partial z$ vary over a wide range, whereas the variations in $\partial P / \partial z$ are quite small so that in many cases a constant value may be used. Appendix A contains a complete discussion of the factors that contribute to pressure at any depth. For general interpretation of sound velocity profiles, however, it is not necessary to consider variations of sea water composition, compressibility of sea water, variation of gravitational forces with depth, or other such factors. $\partial P / \partial z$ may therefore be approximated as 0.10 kgm/cm² per meter of depth.

The sound velocity profiles in figures 7 and 8 are indicative of the effect of pressure variation with depth on sound velocity for various temperatures and salinities. The displacement of the profiles in figure 7 is due to differences in temperature (salinity constant at 35 o/oo). Although the four profiles appear similar, they vary slightly due to differences in $\partial V / \partial P$ at different temperatures. The profiles are really curves and not straight lines because at constant temperature $\partial V / \partial P$ varies with pressure.

The variations of $\partial V / \partial P$ with temperature and pressure are, however, quite small; hence the curves appear to have the same constant slope. Likewise, in figure 8 the profiles for all three values of salinity (temperature constant at 20°C) appear to have similar and constant slopes. There are actually small differences due to variations in $\partial V / \partial P$ with salinity (temperature and pressure constant) and with pressure (temperature and salinity constant). The profiles in figures 7 and 8 show that even if temperature and salinity are constant, sound velocity increases by approximately 17 meters per second for every 1000 meters of depth.

The slope of the sound velocity profile will vary with salinity and temperature gradients. Salinity gradients are considered separately from temperature gradients to illustrate the effect of each independently from the other.

Figure 9 shows the sound velocity profiles for three constant salinity gradients, starting with a salinity of 35 o/oo on the surface (temperature constant at 20°C). The profiles show that a salinity gradient stronger than -.01 o/oo per meter is required to offset the increase in sound velocity due to pressure (depth). The strength of the salinity gradient required for isovelocity (constant velocity) may be calculated from the $\partial V / \partial z$ equation:

$$\frac{\partial V}{\partial z} = \left(\frac{\partial V}{\partial T} \right) \left(\frac{\partial T}{\partial z} \right) + \left(\frac{\partial V}{\partial S} \right) \left(\frac{\partial S}{\partial z} \right) + \left(\frac{\partial V}{\partial P} \right) \left(\frac{\partial P}{\partial z} \right).$$

For isovelocity conditions: $\partial V / \partial z = 0$.

For constant temperature: $\partial T / \partial z = 0$.

Therefore: $(\partial V / \partial T) (\partial T / \partial z) = 0$.

Making these substitutions:

$$0 = \left(\frac{\partial V}{\partial S} \right) \left(\frac{\partial S}{\partial z} \right) + \left(\frac{\partial V}{\partial P} \right) \left(\frac{\partial P}{\partial z} \right).$$

Referring to figure 3: for a salinity of 35 o/oo and a temperature of 20°C, $\partial V / \partial S \approx 1.17$ meters/second per gram/kilogram of salinity (for pressures less than 100 kgm/cm²). Referring to figure 5: for the same conditions, $\partial V / \partial P \approx 0.160$ meters/second per gram/kilogram (for pressures less than 100 kgm/cm²). Substituting these values and the approximation $\partial P / \partial z = 0.10$ into the equation:

$$0 = 1.17 \left(\frac{\partial S}{\partial z} \right) + (.160) (.10).$$

This yields: $\partial S / \partial Z = -0.0137$.

Therefore, under the conditions given, a salinity gradient stronger than -0.0137 o/oo per meter is required to cause sound velocity to decrease with depth.

The effect of constant temperature gradients on the sound velocity profile is shown in figure 10 (salinity constant at 35 o/oo). For a temperature of 20°C at the surface, a temperature gradient of -0.005°C per meter will cause approximate isovelocity. The fact that sound velocity decreases with increasing depth even though the temperature gradient remains constant is due to an increase in $\partial V / \partial T$ with decreasing temperature, causing the $(\partial V / \partial T) (\partial T / \partial Z)$ term to outweigh the $(\partial V / \partial P) (\partial P / \partial Z)$ term, which is not growing so rapidly.

Thus far, variations in sound velocity profiles have been considered in terms of constant temperature or salinity gradients. By considering the sum of one or more temperature and salinity gradients, it is possible to form every type of sound velocity profile found in the ocean. There are several general types of profiles which, with small variations, account for most conditions found. Each type of profile must be considered in detail if general conclusions are to be drawn concerning the relative effects of temperature, salinity and pressure on sound velocity.

Single Minimum

The most frequently observed type of sound velocity profile is the single minimum, in which a single minimum sound velocity occurs at some depth (figure 11). This type of profile may be explained in terms of a very simple set of oceanographic conditions. If salinity is assumed to be constant, a single minimum profile can arise from a uniform temperature gradient, extending from the surface to the depth at which minimum sound velocity occurs and terminating at that depth in a constant temperature layer. A check of the curves and gradients already presented will verify this interpretation and allow calculation of the gradients involved. This analysis presents the overall picture without taking into account very slight salinity gradients or slight changes in the temperature gradient.

The single minimum profile is found in most ocean areas because a temperature gradient from the surface to some depth does exist. This gradient is due to deep water, formed in the arctic or antarctic, which is colder than the water found in most areas of the ocean. Although salinity is not constant in open ocean areas, the range of variation is small and salinity gradients vary but slightly.

Surface Channel

In all sound velocity profiles (noticeable or not) there is a surface sound channel - an area of increasing sound velocity (figure 12) - which results from isothermal and isohaline (constant temperature and salinity) conditions at the surface. This surface layer of isothermal and isohaline water is present at all times in all ocean areas. Thickness of the layer varies from a few millimeters to several hundred meters. These conditions result from the dynamic mixing of water and the layer is often referred to as the mixed layer. Temperature and salinity gradients for which $(\partial V / \partial T) (\partial T / \partial z) + (\partial V / \partial S) (\partial S / \partial z) < (\partial V / \partial P) (\partial P / \partial z)$ may also contribute to the thickness of this surface sound channel.

Surface Channel and Single Minimum

The surface sound channel exists on all sound velocity profiles. Figure 13 shows the surface sound channel on a single minimum profile. The temperature gradient is in three simple sections: a constant temperature layer at the surface, a thermocline or layer in which temperature decreases with depth, and a constant temperature layer at the bottom. Salinity is considered as constant and has no effect on the profile. This is a very common type of profile because the conditions described are common to all water masses.

Double Minimum

Salinity is not always constant. In areas near shore, in bays, and near large ice masses, salinity may vary considerably with depth. When a large positive change in salinity occurs in the thermocline, the sound velocity profile may have two minimums (figures 14 and 15). Sound velocity, which is decreasing with depth in the thermocline, increases with depth in the halocline (salinity gradient). After passing through the halocline, the sound velocity again decreases with depth until the thermocline terminates, at which point it increases due to the pressure effect.

There are two types of profiles with a double minimum: the shallow minimum and the deep minimum. The conditions for both are the same - a layer of relatively fresh water at the surface. The difference is due to the volume of fresh water or thickness of the fresh water layer. A large volume of fresh water - e.g., near a melting ice pack - produces a thick surface layer, and the halocline occurs deep in the thermocline (figure 14). Under these conditions the shallow minimum has a lesser value (in terms of sound velocity) than the deep minimum, because there is insufficient thermocline left below the halocline to produce more of a decrease in sound velocity than has already occurred at the shallow minimum. On the other hand, a small volume of fresh water - e.g., near shore areas with fresh water run-off - produces a thin surface layer so that the halocline occurs shallow in the thermocline. Under these conditions the deep minimum has a lesser value (figure 15).

Kink

If a high saline layer overlays a less saline layer, the result is a kink type of sound velocity profile (figure 16). Such conditions may be found in tropical areas where evaporation exceeds precipitation, or near a river run-off during winter where there is an intrusion of cold fresh water which is denser than the surface waters. This decrease in salinity results in an additional decrease in sound velocity in the halocline, giving the profile a kinked appearance.

CONCLUSION

This report has analyzed the effect on sound velocity of changes in temperature, salinity and pressure, based on Wilson's equation for the variation of sound velocity in sea water. To illustrate this variation a series of graphs have been prepared which show the rate of change of sound velocity with respect to temperature, salinity, pressure, or any combination of these parameters. Typical sound velocity profiles have been presented and interpreted in terms of the environmental conditions that produce them.

By using these graphs and typical profiles, engineers can infer the general oceanographic conditions from sound velocity profiles and determine the strength and extent of temperature and salinity gradients.

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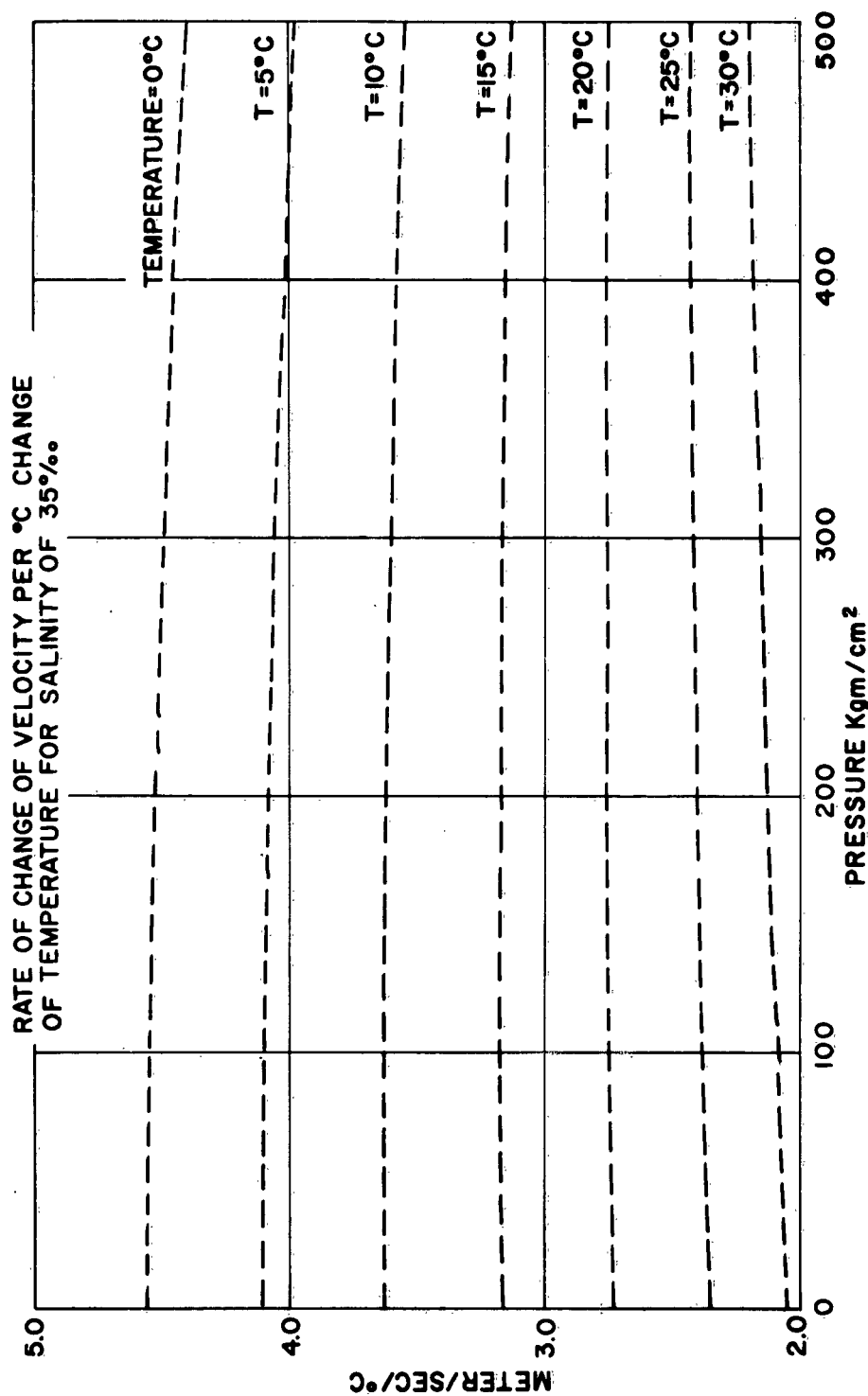


FIGURE 1

Figure 1. Rate of Change of Sound Velocity with Respect to Temperature.

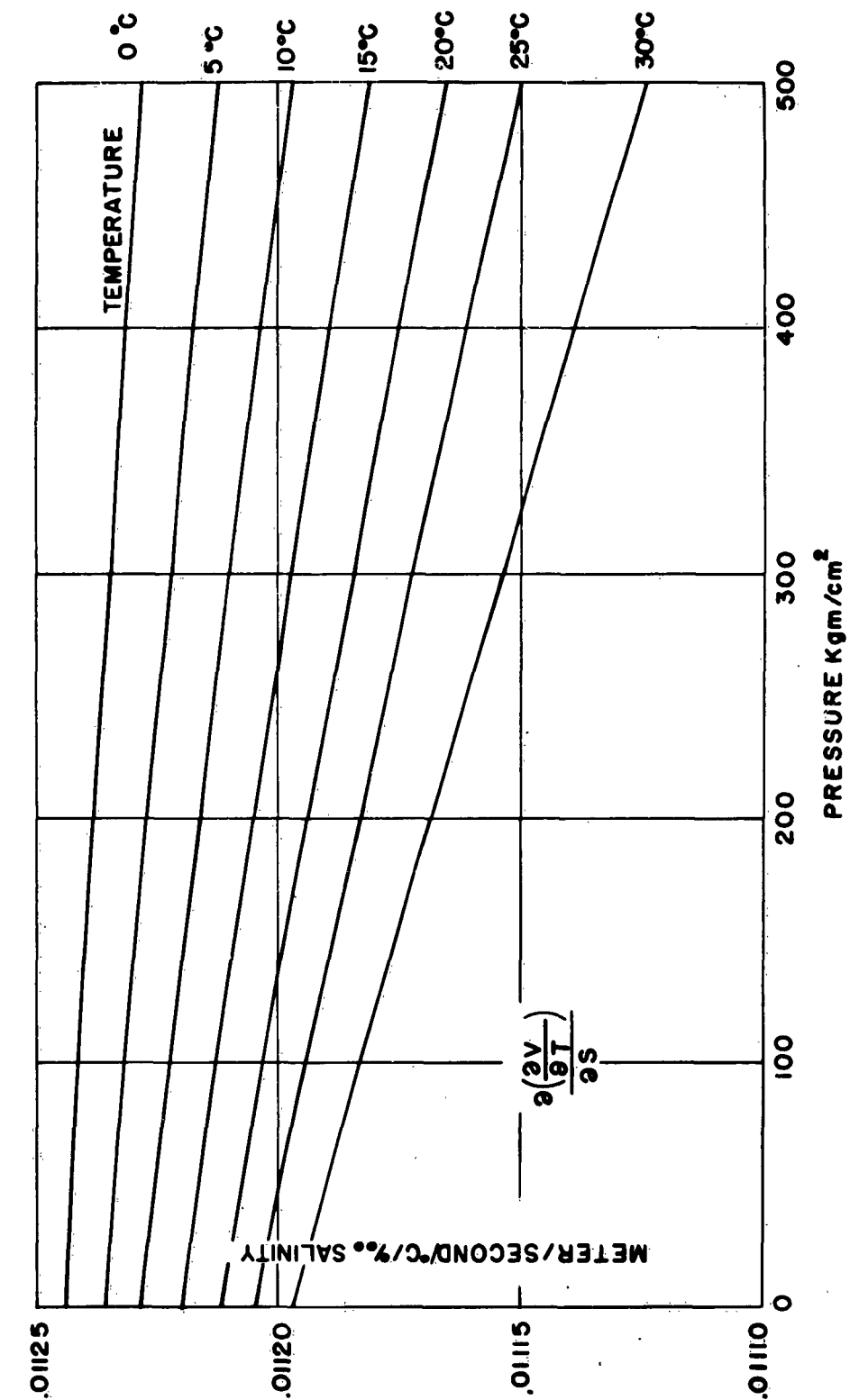


FIGURE 2

Figure 2. Rate of Change of Sound Velocity with Respect to Temperature: Salinity Correction.

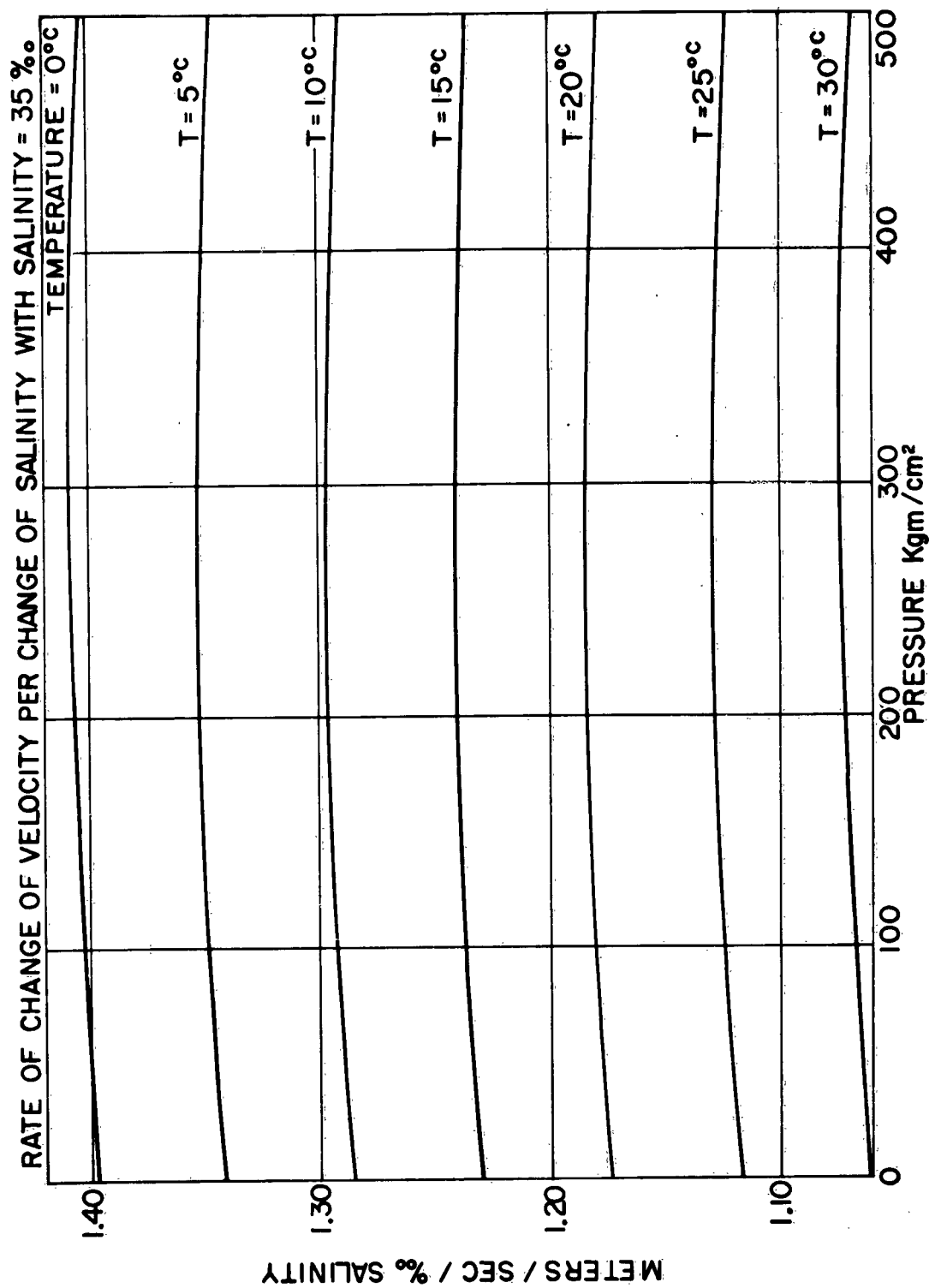


FIGURE 3

Figure 3. Rate of Change of Sound Velocity with Respect to Salinity.

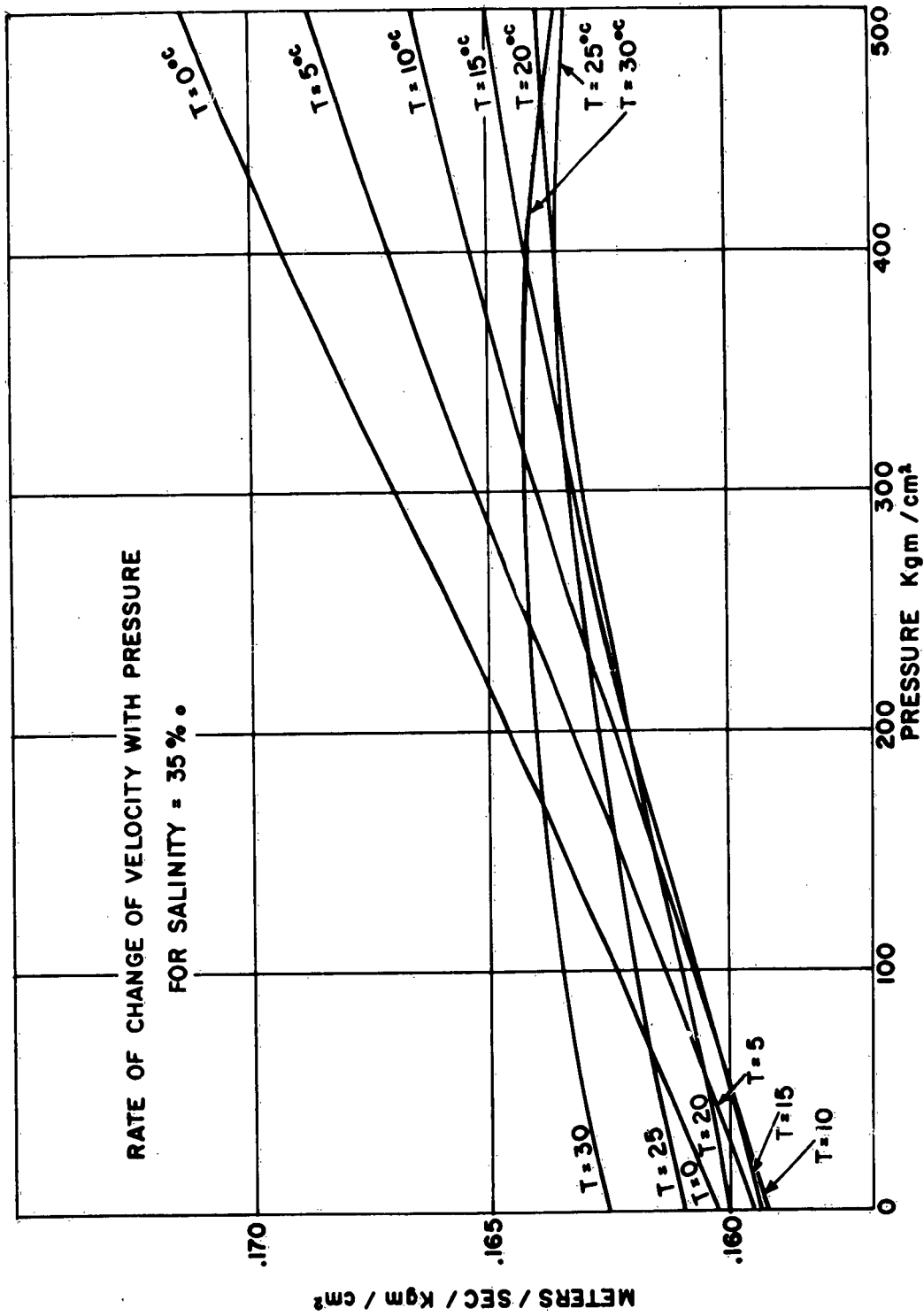


Figure 4. Rate of Change of Sound Velocity with Respect to Pressure.

FIGURE 4

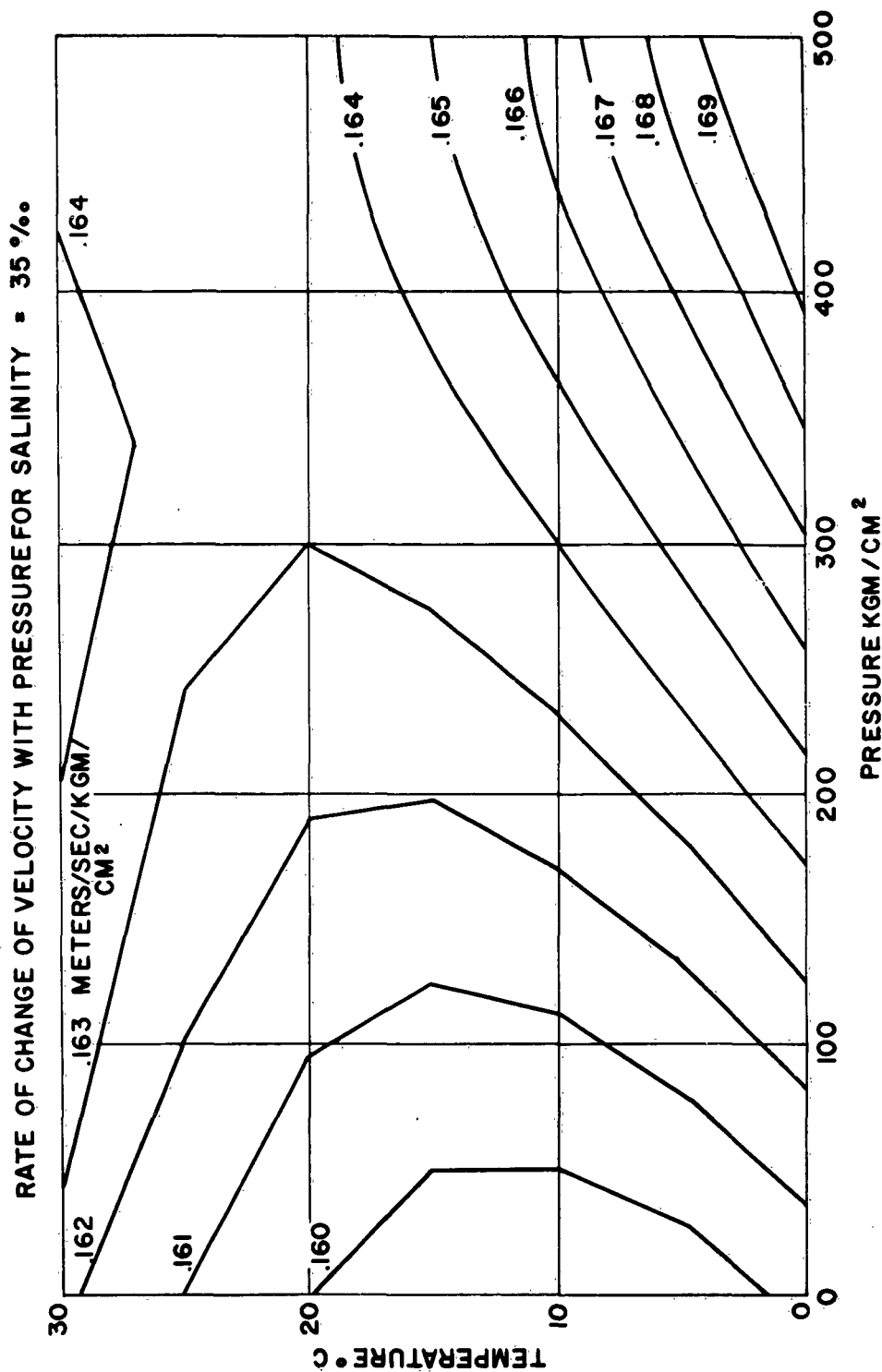


Figure 5. Rate of Change of Sound Velocity with Respect to Pressure.

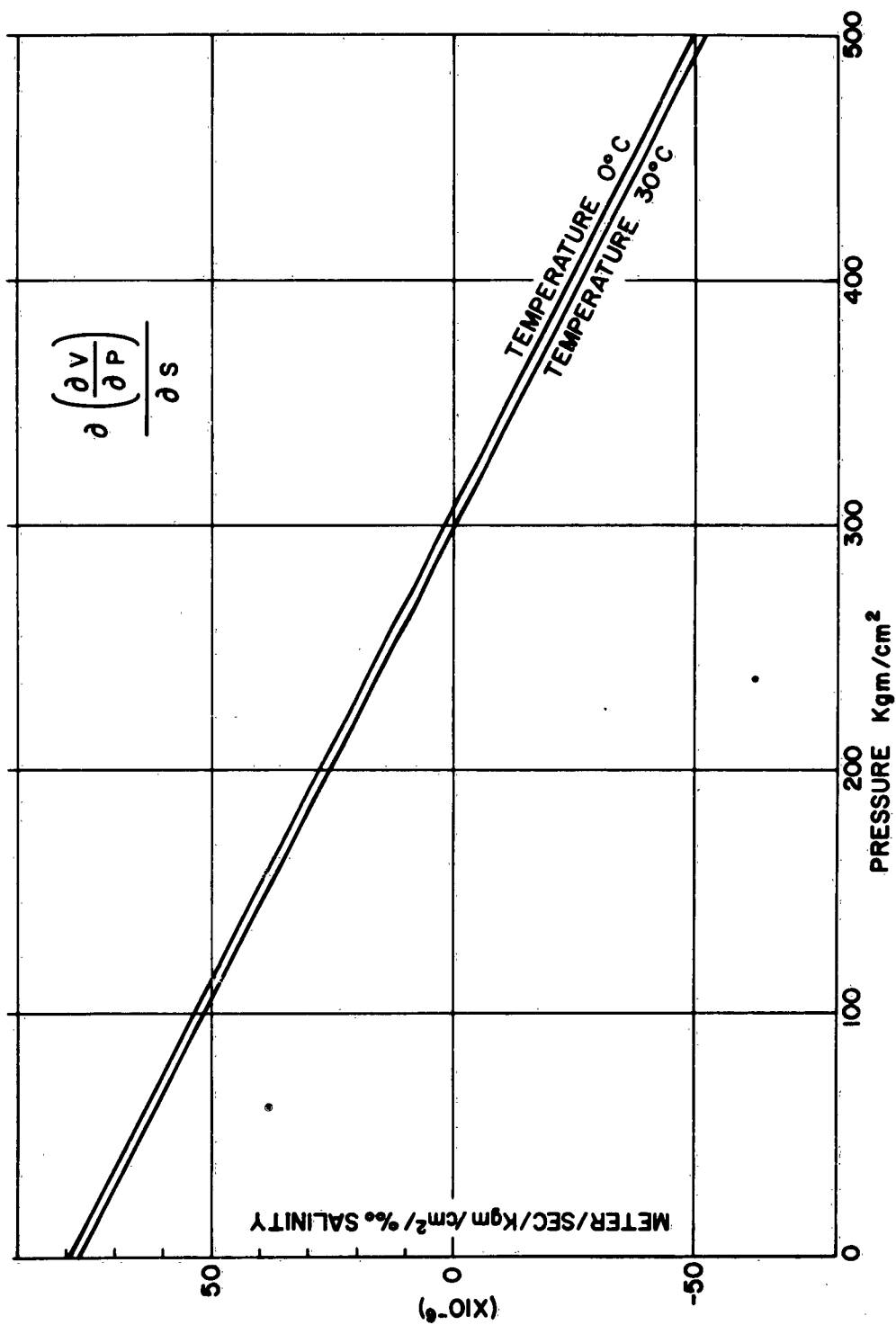


Figure 6. Rate of Change of Sound Velocity with Respect to Pressure: Salinity Correction.

FIGURE 6

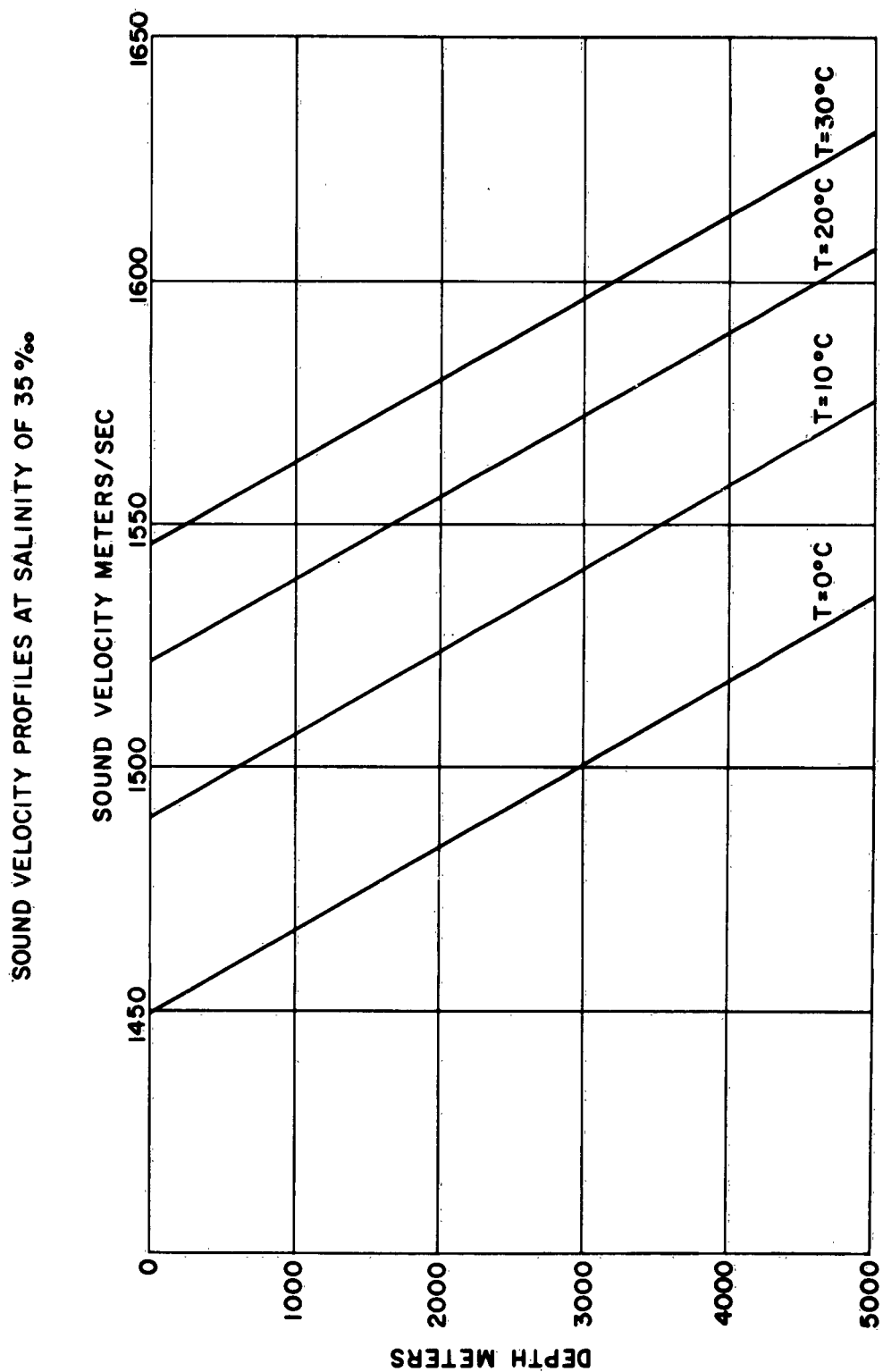


FIGURE 7

Figure 7. Sound Velocity Profiles for Various Constant Temperatures.

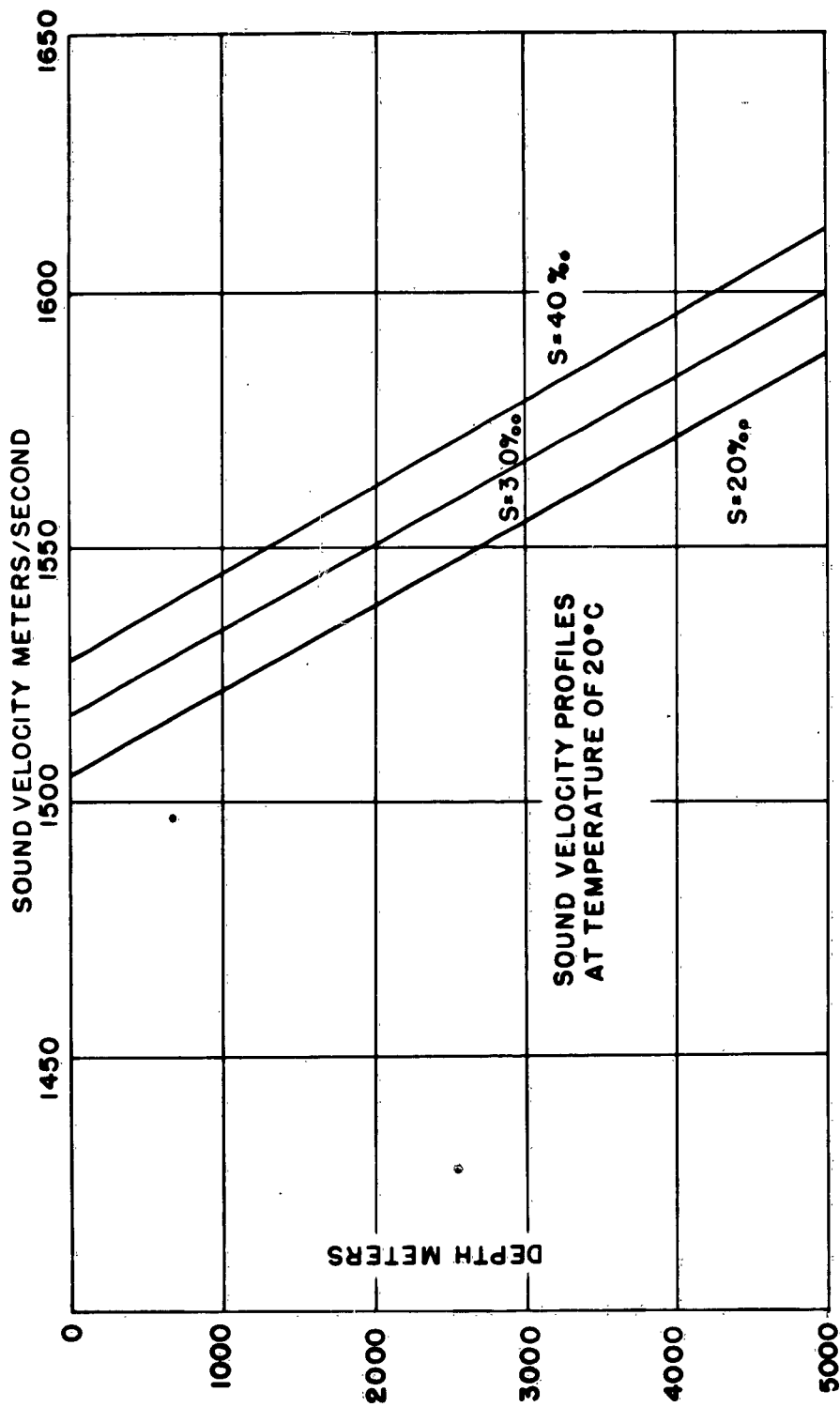


Figure 8. Sound Velocity Profiles for Various Constant Salinities.

FIGURE 8

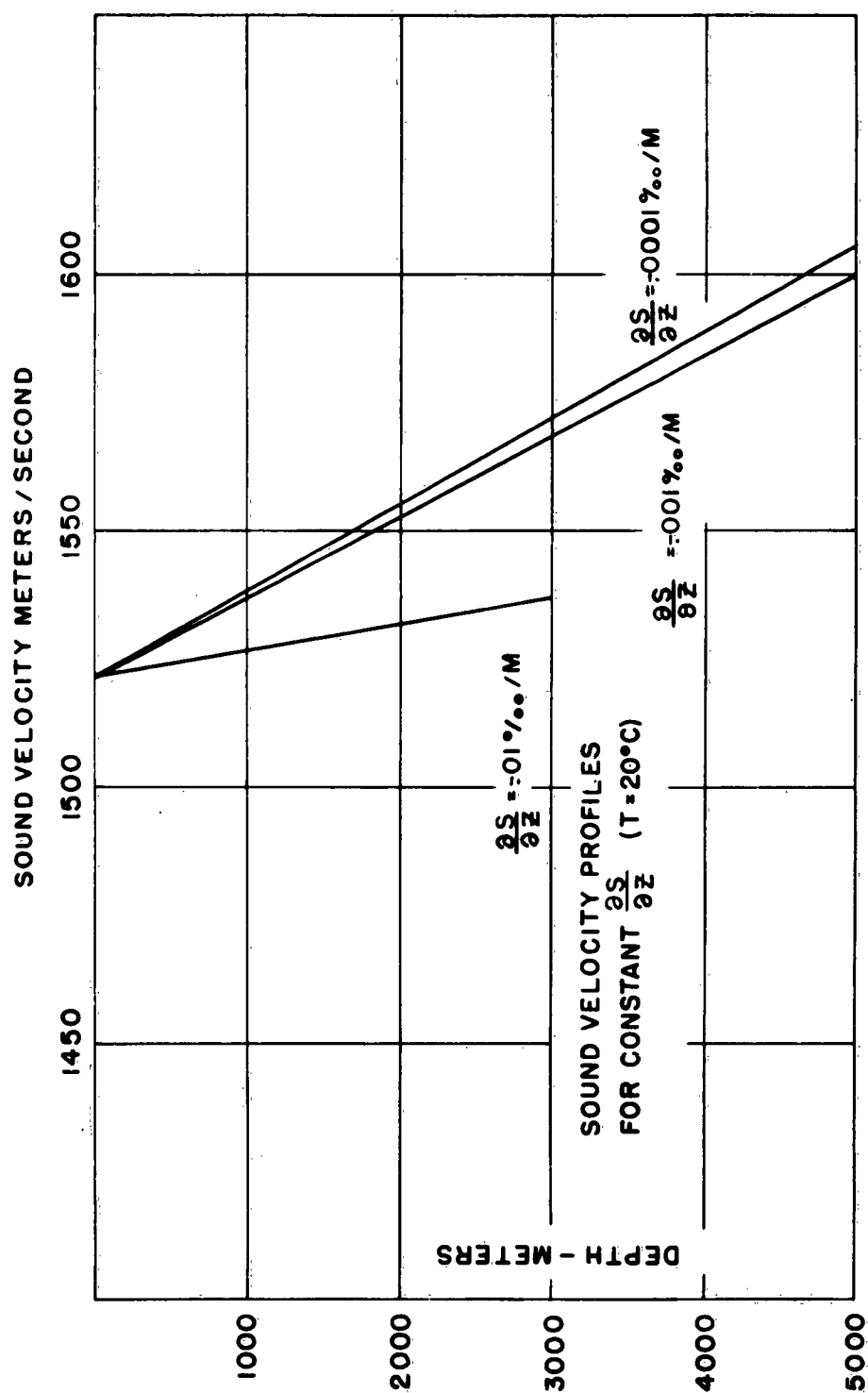


FIGURE 9

Figure 9. Sound Velocity Profiles for Various Salinity Gradients.

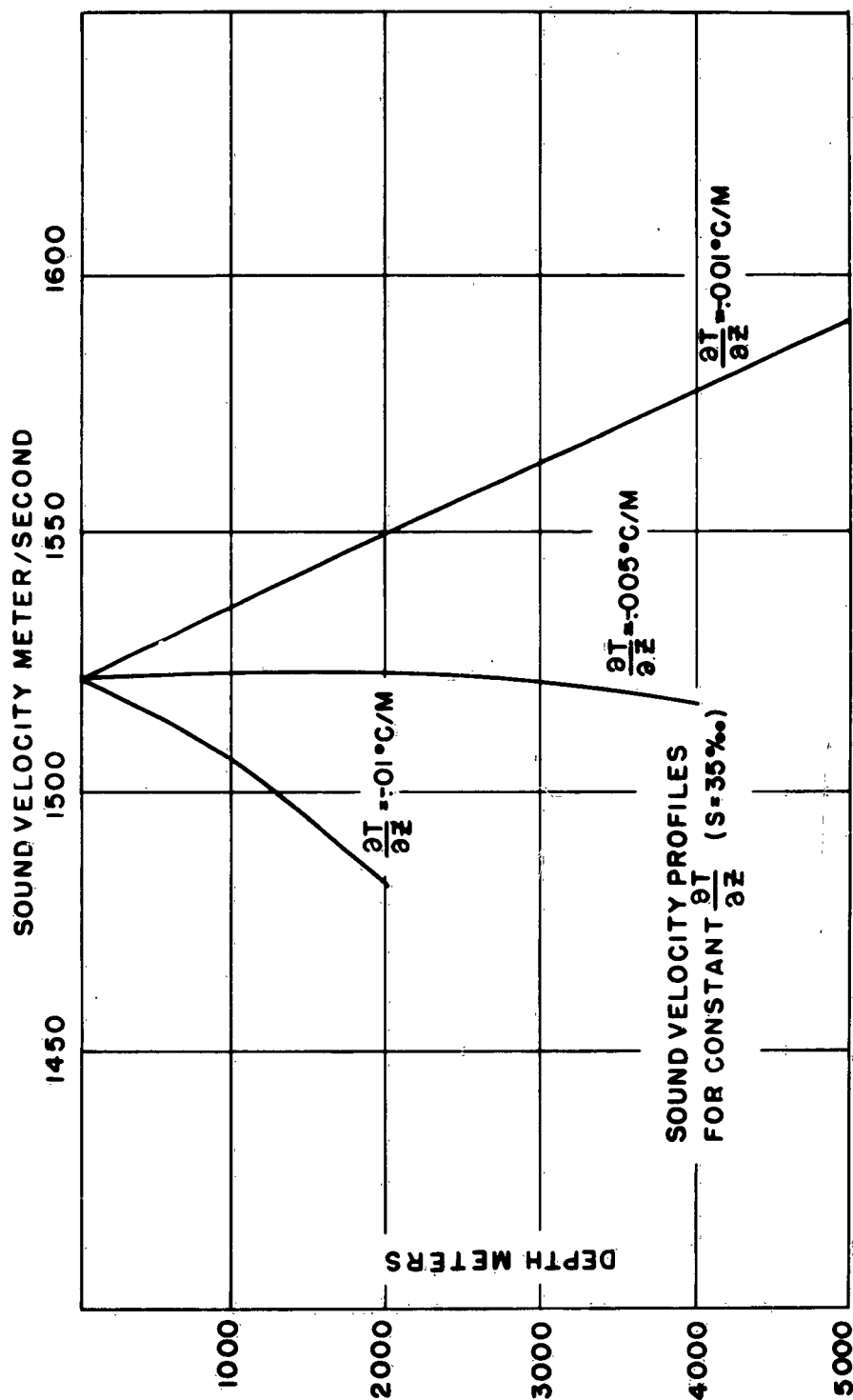


FIGURE 10

Figure 10. Sound Velocity Profiles for Various Temperature Gradients.

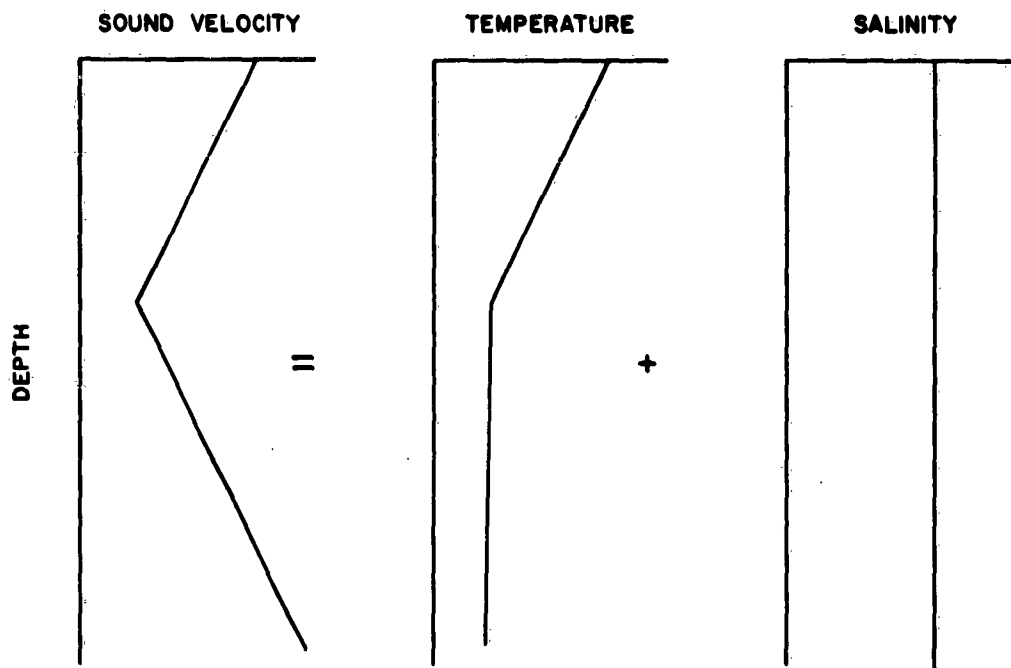


Figure 11. Sound Velocity Profile: Single Minimum.

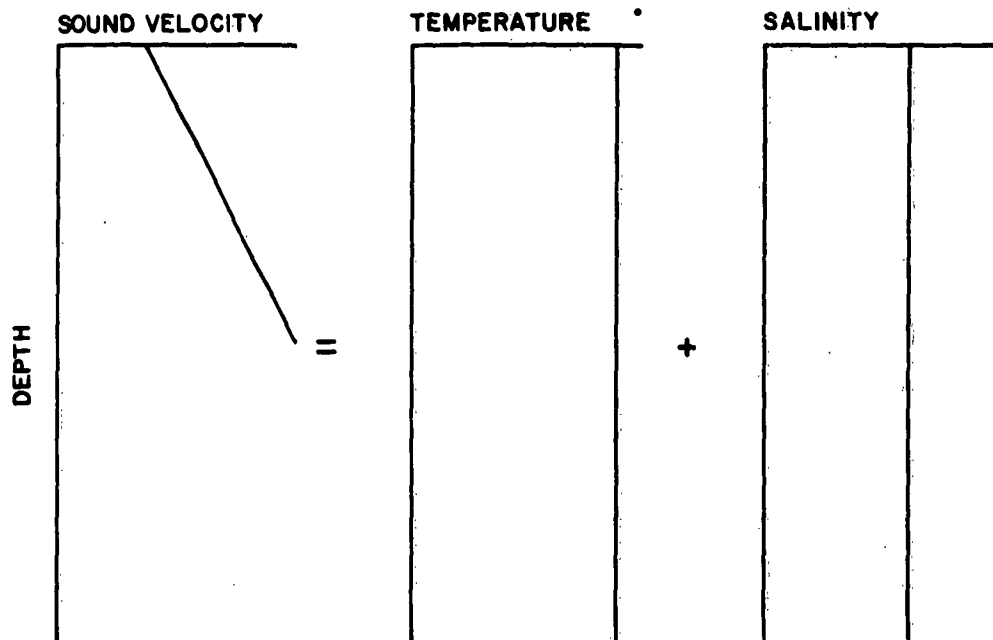


Figure 12. Sound Velocity Profile: Surface Channel.

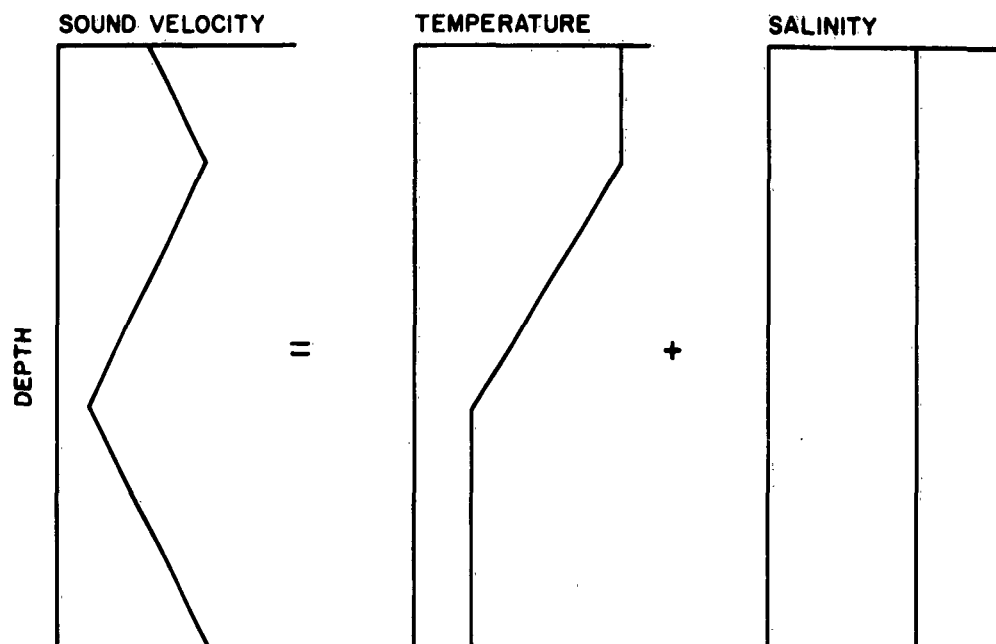


Figure 13. Sound Velocity Profile: Surface Channel and Single Minimum.

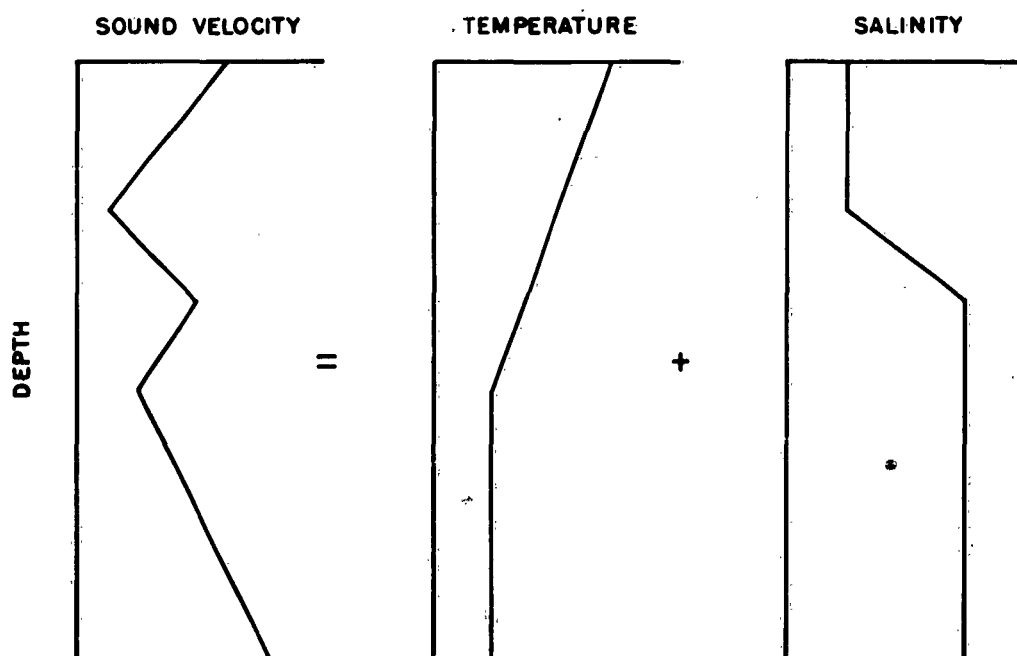


Figure 14. Sound Velocity Profile: Double Minimum Shallow.

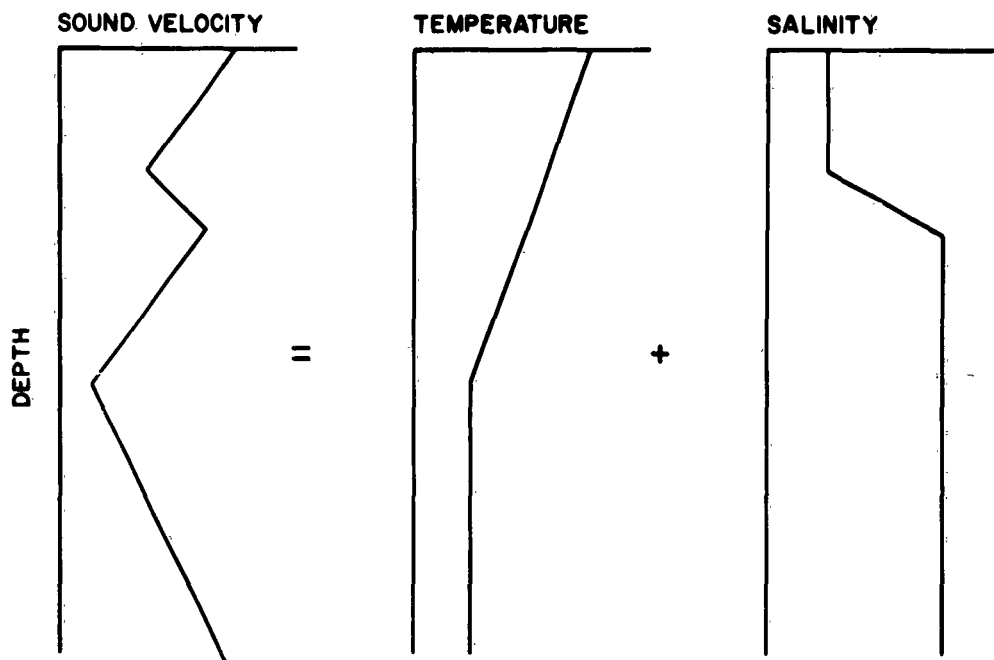


Figure 15. Sound Velocity Profile: Double Minimum Deep.

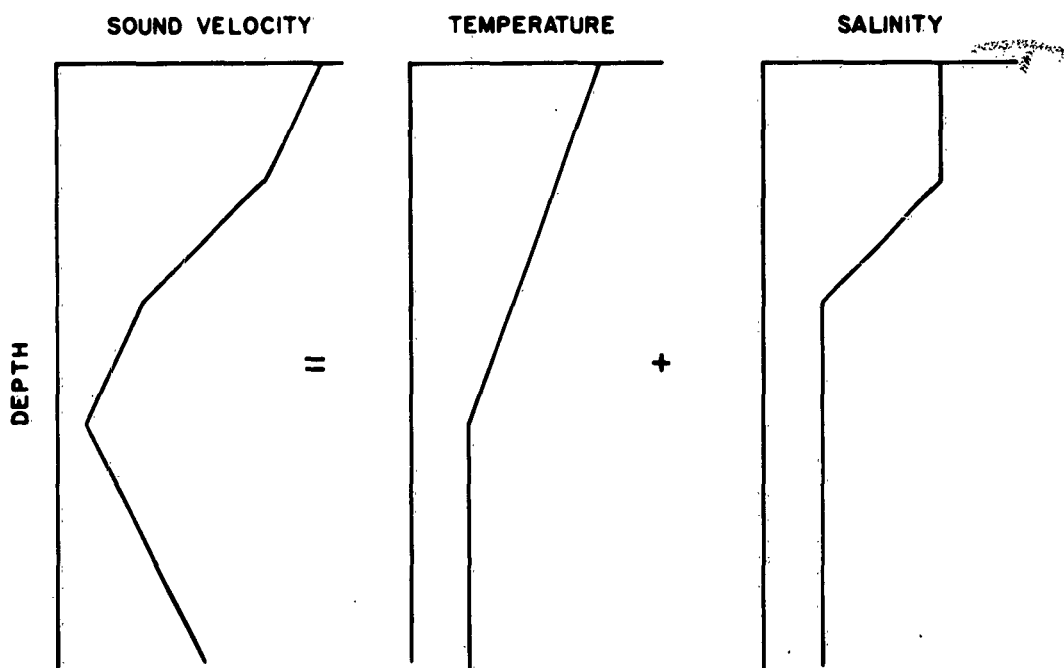


Figure 16. Sound Velocity Profile: Kink.

APPENDIX A

(Material in this appendix is based on NUOS Technical Memorandum No. 284, "Processing Oceanographic Station Data Using Rapid Data-Handling Equipment", C. F. Morey, U. S. Naval Underwater Ordnance Station, August 1962. For references to formulas and publications see this earlier report.)

To compute the velocity of sound in sea water according to the formulas developed by Wayne D. Wilson (which give velocity as a function of temperature, salinity and pressure), the pressure must be calculated from the observed oceanographic station data. The pressure at any point in a fluid is the sum of the atmospheric and hydrostatic pressures. Hydrostatic pressure is given by:

$$P_h = \int_0^z \rho g \, dz$$

where: P_h = hydrostatic pressure in newtons/cm².

ρ = density in kgm/cm³.

g = gravitational acceleration in cm/sec².

z = depth in meters.

A method for evaluating this equation for the pressure in a non-homogeneous compressible fluid in a non-uniform gravitational field has been expressed by N. P. Fofonoff and N. A. Pedersen. This method has been adopted with modifications by the Naval Underwater Ordnance Station for calculating pressure in the ocean from oceanographic station data.

The geographic variation of gravitational acceleration is best expressed by the formula accepted by the General Assembly of the International Union of Geodesy and Geophysics at Stockholm, Sweden in 1930. This formula is:

$$g_0 = 978.049 (1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 \phi)$$

where: g_0 = gravitational acceleration at sea level in cm/sec².

ϕ = latitude in degrees.

The variation of gravitational acceleration with depth has been given by Sverdeep as:

$$g = g_0 + 2.202 \times 10^{-4} z$$

This expression has been verified by measurements made in the bathyscaph TRIESTE by K. V. Mackenzie.

V. W. Ekman has expressed the variation in density as a function of temperature, salinity and pressure. The complete functional relationship between these quantities, which is very complex, is expressed here in terms of functions which are frequently computed in oceanographic station work.

$$\rho_{S,T,P} = \frac{1}{\alpha_{S,T,P}}$$

where: $\rho_{S,T,P}$ = density as a function of salinity, temperature and pressure.

$\alpha_{S,T,P}$ = specific volume as a function of salinity, temperature and pressure.

The specific volume is expressed as:

$$\alpha_{S,T,P} = \alpha_{S,T,0} - P \alpha_{S,T,0} 10^{-9} \left[\frac{4.886 \times 10^3}{1 + 1.83 \times 10^{-5} P} + (A + B) \right]$$

where: $A = P(10^{-4})[105.5 + 9.5T - 0.158T^2] - 1.5P^2T(10^{-8})$

$$- [227 + 28.33T - 0.551T^2 + 0.004T^3].$$

$$B = - \frac{\sigma_0 + K}{10} [147.3 - 2.72T + 0.04T^2 - P(10^{-4})(32.4 - 0.87T + 0.02T^2)]$$

$$+ \left(\frac{\sigma_0 + K}{10} \right)^2 [4.5 - 0.1T - P(10^{-4})(1.8 - 0.06T)]$$

$$K = -28.134$$

$$\alpha_{S,T,0} = \frac{1}{1 + \sigma_T(10^{-3})}$$

$$\sigma_T = \Sigma_T + (\sigma_0 + 0.1324)[1 - M_T + N_T(\sigma_0 - 0.1324)]$$

$$\Sigma_T = - \left[\frac{(T - 3.98)^2}{503.570} \right] \left[\frac{T + 283}{T + 67.26} \right]$$

$$M_T = T(4.7867 - 0.098185T + 0.0010843T^2)10^{-3}$$

$$N_T = T(18.03 - 0.8164T + 0.01667T^2)10^{-6}$$

$$\sigma_0 = -0.069 + 1.4708Cl - 0.00157Cl^2 + 0.0000398Cl^3$$

$$Cl = \frac{S - 0.030}{1.8050}$$

The expression for calculating the density, which is required for the pressure calculation, itself requires that pressure be known. This difficulty may be overcome by an iterative process commonly used in mathematics. An approximation of the pressure is made in order to determine density and then pressure. The computed pressure is compared with the approximation used. If they do not agree within certain limits, the process is repeated using the computed pressure as the new approximation to determine again the density and pressure. This process is repeated until agreement is reached between the approximated and computed pressures.

The first approximation for pressure is computed as:

$$P = \int_0^Z g(1 + \bar{\sigma}_T \times 10^{-3}) dZ$$

where: $\bar{\sigma}_T$ = average σ_T .

Computation of the pressure is further complicated by the fact that oceanographic station data consist of a number of unique samples taken in the water column, and not a continuous record of temperature, salinity and depth. With this data the trapezoidal rule is used successively for evaluating the pressure integral:

$$P_i = \int_0^Z \rho g dZ = 1/4 \sum_{i=1}^n (\rho_i + \rho_{i-1})(g_i + g_{i-1})(Z_i - Z_{i-1}).$$

Using this process the pressure approximation becomes:

$$P_i = P_{i-1} + 1/4 \left\{ \left[2 + (\sigma_{t_i} + \sigma_{t_{i-1}}) 10^{-3} \right] (g_i + g_{i-1})(Z_i - Z_{i-1}) \right\}.$$

Once the hydrostatic pressure has been determined in newtons/cm², the pressure for computation of sound velocity may be obtained simply by adding the atmospheric pressure (1 millibar = 10⁻² newtons/cm²). This pressure must be converted to kilograms/cm² by multiplying by 1/9.80665 kilogram per newton. Wilson's formula for sound velocity can then be used:

$$V = 1449.14 + \Delta V_T + \Delta V_P + \Delta V_S + \Delta V_{STP}.$$

$$\Delta V_T = 4.5721T - 4.4531 \times 10^{-2}T^2 - 2.6045 \times 10^{-4}T^3 + 7.9851 \times 10^{-6}T^4.$$

$$\Delta V_P = 1.60272 \times 10^{-1}P + 1.0268 \times 10^{-5}P^2 + 3.5216 \times 10^{-9}P^3 - 3.3606 \times 10^{-12}P^4.$$

$$\Delta V_S = 1.39799(S-35) + 1.6920 \times 10^{-3}(S-35)^2.$$

$$\begin{aligned}\Delta V_{STP} = & (S-35) (- 1.1244 \times 10^{-2}T + 7.7711 \times 10^{-7}T^2 + 7.7016 \times 10^{-5}P \\ & + 1.2943 \times 10^{-7}P^2 + 3.1580 \times 10^{-8}PT + 1.5790 \times 10^{-9}PT^2) \\ & + P(- 1.8607 \times 10^{-4}T + 7.4812 \times 10^{-6}T^2 + 4.5283 \times 10^{-8}T^3) \\ & + P^2(- 2.5294 \times 10^{-7}T + 1.8563 \times 10^{-9}T^2) + P^3(- 1.9646 \times 10^{-10}T).\end{aligned}$$

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