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Correction of Reversing Thermometers and Related
Depth Calculations in Baltic Water.

by

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Abstract.

There has been some problems to calculate depth by means of the
revering thermometer, mostly depending on the error of the ther-
mometers. In this paper an effort has been made to recall most of
the conceivable errors and to make them as small as possible. The
main problem has been the calibration of the thermometers. Special
stress is laid upon the practical elaboration with a thermostated
bath. Mean values of density, $\mathcal{S}_m$, to be used in depth calcu-
lations in the seas around Sweden are presented.

1. Introduction.

The reversing thermometer is the most important instrument used to obtain temperature at a fixed depth. It was first constructed by Negretti and Zamba in 1878, (Dietrich 1967). The instrument consists of two thermometers, one main thermometer which register temperature at reversal and one auxilliary thermometer used to correct the main thermometer, when reading is done. There are two types of reversing thermometers, protected and unprotected. The protected one is used to measure temperatures. The unprotected thermometer is used in combination with the protected one to calculate the depth. Both types of thermometers have precision and technique in common.

2. Calibration.

In order to utilize the precision, the thermometer requires a continous calibration of its capillary and scale. When measuring temperatures in the sea, an accuracy of $\pm$ 0.01 °C is often required. In order to compute the depth with an error less than 0.5 %, the temperature error must not be larger than $\pm$ 0.01 °C. These requirements of accuracy lead to optimum experimental conditions at the calibration.

2.1. The Scale Error.

Even if there is a large scale error, the thermometer can bee used as a precision instrument (F.S.J. 1962), since the error will be corrected at the calibration.

2.2. The Capillary Error.

A thermometer is "aging" with time. This depends on two facts. First we have the amorphous property of the glass, secondly the oxidation of mercury. The amorphous behaviour of glass leads to a change of the capillary diameter.

It is not possible to get total vacuum in the capillary. Therefore we always have an oxidation at the end of the mercury column.

This is a rather big problem for the reversing thermometer. Every oxide impurity of the mercury can cause the column not to break at the exact point. The error caused in this way will not be systematic, it will change from time to time. Some thermometers can have fluctuations up to $\pm$ 0.1 °C at repeated reversings and must therefore be rejected. Normally there are fluctuations of $\pm$ 0.01 °C as Table 1 shows.

2.3. The Calibration Reference.

In order to know at which exact temperature the reversing thermometers are calibrated we need a temperature measring instrument with an error less than 0.005 °C and a long-term stability. Under practical conditions a gas thermometer will have too large an error of measurement. The electronic instruments (thermistor or thermocouple) have to be calibrated from time to time due to aging. This fact makes these instruments less suitable for this purpose.

The easiest way is to use a mercury calorimeter devided in hundreds and calibrated in thousends. Such a calorimeter is "aged" before the calibration. The capillary has also been well cleaned in order to avoid oxidation of the mercury. The only thing we have to consider, is to correct for the mercury column above the water surface. This is done by the following equations:

$$t = t_a + t_{corr}$$
$$t_{corr} = \frac{n}{K} \left(t_a - t_p \right)$$

(Fig. 1.)

K = reciprocal thermal expansion coefficient of the thermometer
   system. (About 6000 °C)

2.4. Thermostat Bath.

At the calibration it is of great importance that the reference calorimeter and all reversing thermometers which shall be calibrated are at the same temperatur. This we obtain with a termostate bath with well mixed water. Measurement showed that with a refrigerating coil and an immerser coupled to a thermal relay in a bath of a size of 120 l, there was a temperature gradient of up to 0.06 °C in the horizontal plane, (Fig. 2.). This can be avoided in the following

way. When a suitable temperature has been reached, the refrigerating coil and the immerser are shut off and the bath remains under vigorous stirring for about 15 minutes before a reading is made.

2.5. Calibration Formula.

When reading the reversing thermometer the temperature is different from that at which it was reversed in the sea. This means, that the mercury and the glass have expanded. For this a correction has to be made. There has been a few different formulas for this, the most exact one made by Svedrup (1947). It starts from the expression

$$C = \frac{(T_w - t)\ (T_w + V_o)}{K}$$

In the evaluation below, the following symbols will be used:

$T' =$ reading of the protected reversing thermometer.

$t =$ temperatur at which protected reversing thermometer is read. i.e. reading of the auxiliary thermometer.

$T_w =$ water temperature in situ.

$T'_u =$ reading of the unprotected reversing thermometer.

$t_u =$ temperature at which unprotected thermometer is read, i.e., reading of the auxiliar thermometer.

$T_u =$ corrected reading of the unprotected reversing thermometer.

$C =$ correction for thermal expansion of the thermometer system subsequent to reversal.

$V_o =$ volume of mercury below the 0°C mark, at 0°C. Temperature, in the reversal thermometer, expressed in degrees centigrades of the scale.

$K =$ reciprocal thermal expansion coefficient of the thermometer system. This is a constant which depends upon the type of glass of which the thermometer is made. The value of K is given on the thermometer expressed in degrees centigrade.

Svedrup replace the unknown T_w with $T' + C$. Making this substitution in the exact expression we get

$$C = \frac{(T' + V_O + C) (T' - t + C)}{K} =$$

$$= \frac{(T' + V_O) (T' - t)}{K} + C \cdot \left[\frac{(T' + V_O) + (T' - t)}{K} \right] + \frac{C^2}{K}$$

The last term may be neglected (never larger than 0.00015 °C) :

$$C = \frac{(T' + V_O) (T' - t)}{K - (T' + V_O) - (T' - t)}$$

In the fraction above, K is either about 6100 or about 6300 °C , depending upon glass quality. (Hansen 1934).

In the sum $-(T' + V_O) - T' + t = -2T' - V_O + t$

we can assume that $2T' = t$ with an error less than 20 °C.

Then we arrive at
$$C = \frac{(T' + V_O) (T' - t)}{K - V_O}$$

with an error less than 0.001 °C .

The unprotected thermometer has the same initial expression :

$$C = \frac{(T_u + V_O) (T_w - t_u)}{K}$$

If we let $T_u = T_u' + C$ then

$$C = \frac{(T_u' + V_O) (T_w - t_u)}{K - (T_w - t_u)}$$

We have already determined the value of T_w with the protected thermometer. Here $T_w - t_u$ never gets larger than 30 °C and we can neglect it in comparison with K.

$$C = \frac{(T_u' + V_O) (T_w - t_u)}{K}$$

2.5.1. Graph.

In order to solve this correction formulas in a quick way we often use graphs (Theisen 1947). Nowadays it is possible to make all this with a computer. This is very useful when depths are to be calculated, because in the formula for calculation of depth a high accuracy of the temperature is needed to get a good result.

3. Calculation of Depth.

The depth of reversal of the thermometer is usually found by directly applying the formula (Anon. 1957).

$$D = \frac{(T_u - T_w)}{\varsigma_m \cdot Q}$$

The temperature T_u and T_w are already known and calibrated. Q is a pressure coefficient of the unprotected thermometer, expressed in degrees centigrades increase of the reading per 0.1 kg/cm^2 increase of pressure. Q is given on the thermometer calibration certificate. The only unknown parameter is the density of the water column above the level of reversal (ς_m). There may be some problems calculating this. The value of density at a specific depth (ς_d) can be calculated with help of hydrographical tables. This is rather laborious and instead a nomogram calculated from the tables can be used. With this method we loose some precision but as we shall see later that does not matter. To get ς_m , the density in situ (ς_d) may be plotted against depth and numerical integration from the surface to each required depth gives the average value.
Again we consider the formula

$$D = \frac{(T_u - T_w)}{Q \cdot \varsigma_m}$$

We know that there is an error in each of the temperatures of $\pm$ 0.01 °C , consequently $T_u - T_w = \pm$ 0.02 °C. As ς_m is nearly unity and $Q \simeq 0.01$, each 0.01 °C corresponds to approximately one meter. Thous ΔD due to temperature errors is equal to $\pm$ 2 meter. To get D with an error depending on ς_m less than 0.5 % it is enough with $\Delta \varsigma_m = \pm$ 0.001 g/cm^3 . In the density nomogram

$\mathcal{S}_d$ is read with four decimals. The consequense of this discussion is that the temperature error dominates the error of depth. As we can accept some error in the value of $\mathcal{S}_m$ it is enough to calculate a mean value for different areas in the sea. This has been done for some water masses surrounding Sweden :

The Skagerrak :

Depth	$\mathcal{S}_m$ (g/cm^3)	$\Delta\mathcal{S}_m$ (g/cm^3)	ΔD (m) (depending on $\Delta\mathcal{S}_m$)
100	1.0267	± 0.0004	± 0.1
200	1.0270	± 0.0004	± 0.1
300	1.0272	± 0.0003	± 0.1
400	1.0273	± 0.0003	± 0.2
500	1.0274	± 0.0003	± 0.2
600	1.0275	± 0.0002	± 0.2

The Baltic :

Depth	$\mathcal{S}_m$ (g/cm^3)	$\Delta\mathcal{S}_m$ (g/cm^3)	ΔD (m) (depending on $\Delta\mathcal{S}_m$)
100	1.0072	± 0.0005	± 0.1
200	1.0080	± 0.0004	± 0.1
300	1.0082	± 0.0004	± 0.2
400	1.0083	± 0.0004	± 0.2

The Gulf of Bothnia :

Depth	$\mathcal{S}_m$ (g/cm^3)	$\Delta\mathcal{S}_m$ (g/cm^3)	ΔD (m) (depending on $\Delta\mathcal{S}_m$)
100	1.0050	± 0.0005	± 0.1
200	1.0055	± 0.0005	± 0.1
300	1.0056	± 0.0005	± 0.2

$\Delta\mathcal{S}_m$ is the normal yearly difference from the mean density $\mathcal{S}_m$. When there are very large saltwater inflows in to the Baltic, the density can arise as much as 0.001 g/cm^3. As we can see, the error of $\mathcal{S}_m$ is smaller at greater depths. This means that when calculating the depth from this values, the error does not increase as fast as may be expected.

Conclusions

When calibrating a reversing thermometer, it is of great importance
that no temperature gradient exists in the thermostate bath. To get
a temperature gradient less than 0.01 °C the following method is used.
When a suitable temperature is received, both the immerser and the
refrigerating coil are shut of. After about 15 minutes stirring at
this temperature, the reversing thermometers as well as a mercury
calorimeter are read.

To correct for the change between the reversing temperature and the
temperature when the thermometers are read, the formula by Sverdrup,
slightly simplified will read

$$C = \frac{(T' + V_o)\ (T' - t)}{K - V_o}$$

with an error from the original expression less than 0.001 °C.

When calculation of depth is carried out with the use of reversing
thermometers, the following formula is used:

$$D = \frac{T_u - T_w}{Q \cdot \mathcal{S}_m}$$

In this calculations the temperatures are the dominating sources of
error. Therefore it is enough to use mean values of the density at
separate areas in the sea.

Table 1.

Temperatur readings at repeated reversing of some reversing thermometers. All temperatures in degrees centigrades.

Ref. temp.	Reversing thermometers No.				
	1	2	3	4	5
17.41	17.50	17.58	17.50	17.51	17.40
17.51	17.58	17.68	17.59	17.69	17.50
17.61	17.69	17.70	17.70	17.77	17.60
17.70	17.78	17.79	17.78	17.80	17.69
17.81	17.89	17.90	17.89	17.89	17.80
18.31	18.39	18.40	18.39	18.40	18.30
18.41	18.49	18.50	18.48	18.53	18.40
18.63	18.71	18.72	18.70	18.72	18.63

Temperature difference between reference temperature and the temperature of the reversing thermometers.

17.41	−0.09	−0.17	−0.09	−0.10	+0.01
17.51	−0.07	−0.17	−0.08	−0.18	+0.01
17.61	−0.08	−0.19	−0.09	−0.16	+0.01
17.70	−0.08	−0.19	−0.08	−0.10	+0.01
17.81	−0.08	−0.19	−0.08	−0.08	+0.01
18.31	−0.08	−0.19	−0.07	−0.09	+0.01
18.41	−0.08	−0.19	−0.07	−0.12	+0.01
18.63	−0.08	−0.19	−0.07	−0.09	+0.01

Fig. 1

Temperature correction for a mercury column above the water surface.

$$t = t_a + t_{corr}$$

$$t_{corr} = \frac{n}{K} (t_a - t_p)$$

Fig. 2

immerser + thermal relay

refrigerating coil
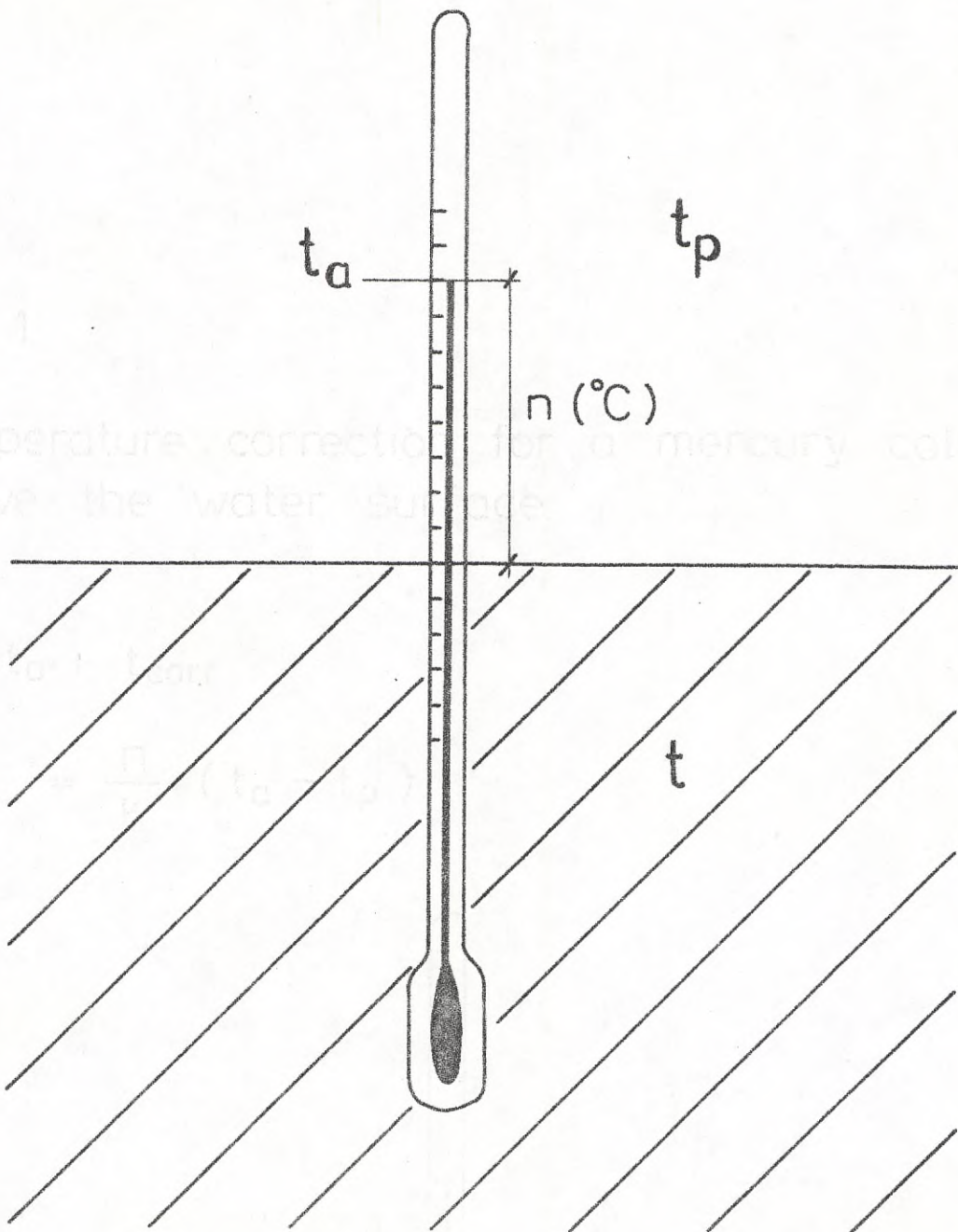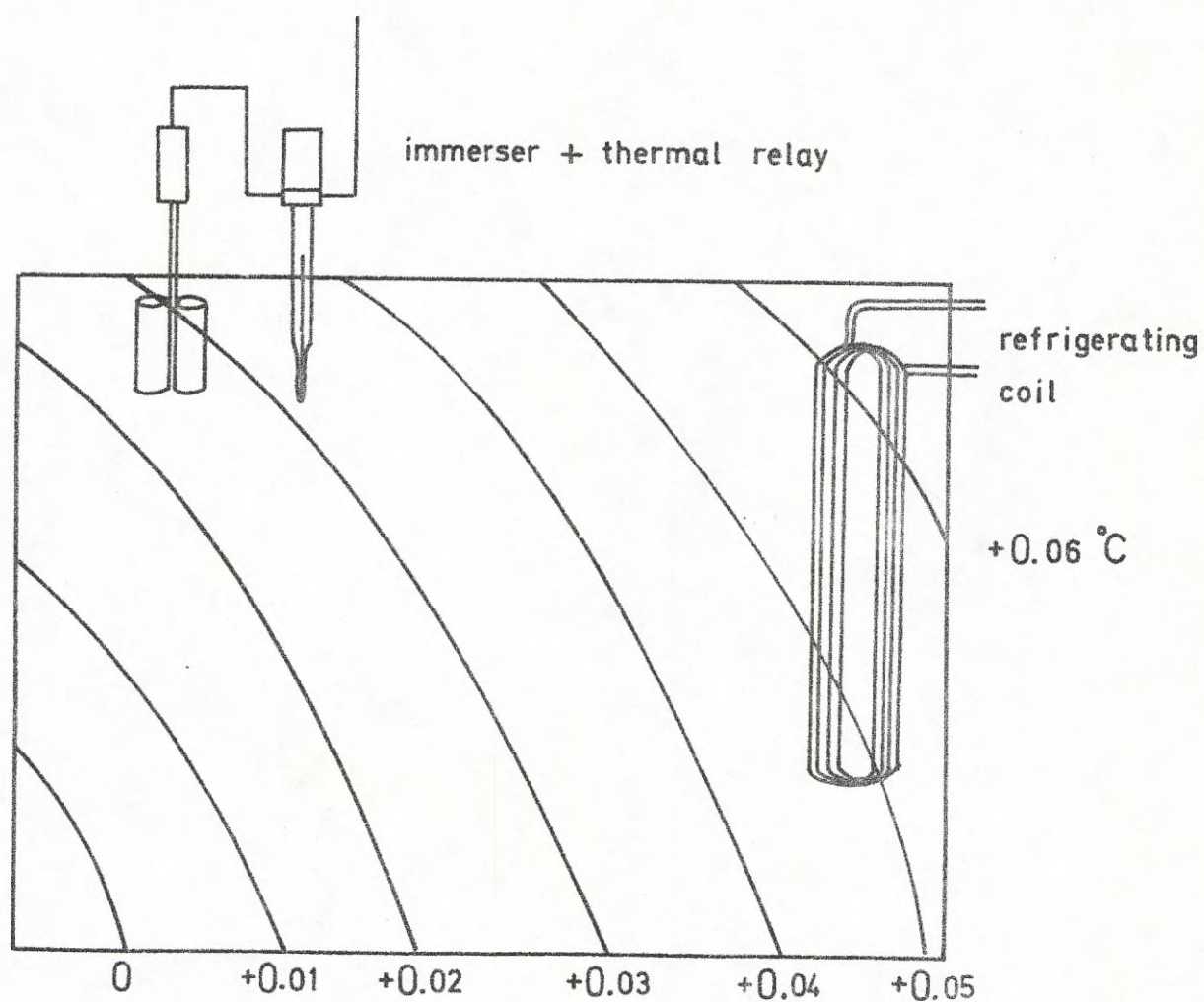
+0.06 °C

0   +0.01   +0.02   +0.03   +0.04   +0.05

The horisontal variation of temperature in the termostate bath.

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