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# NOTES ON THE DEVELOPMENT OF A THERMISTOR TEMPERATURE PROFILE RECORDER (TPR)

By

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## ABSTRACT

A vertical temperature profile recorder, utilizing a thermistor as the temperature sensing element, has been developed for use on lakes, bays, or other enclosed or semi-enclosed bodies of water where temperature profiles in the upper 30 m are desired. Tests of the instrument indicate that it is rugged and durable, giving easily readable records accurate to ± 0.1° C. The response factor of the composite instrument (thermistor, amplifier, and recorder) is 1.4 seconds. To obtain maximum accuracy, the instrument must be lowered at a rate compatable with the magnitude of the temperature gradient; that is, the larger the gradient the slower must be the rate of lowering. Since depth is recorded by measuring the amount of paid-out cable, its use is restricted to conditions of zero wire angle.

In connection with the prosecution of the Lake Mead Water Loss Investigations, being conducted jointly by the U. S. Navy Electronics Laboratory (NEL), U. S. Geological Survey, U. S. Bureau of Reclamation, and U. S. Weather Bureau, it was necessary to develop a portable instrument for obtaining vertical temperature profiles to a maximum depth of 30 m. The instrument was designed for use on lakes, bays, or other enclosed or semi-enclosed bodies of water where wind-wave, swell, and surface currents are at a minimum. This instrument may have application to various problems in physical, chemical, and biological limnology and in estuarian oceanography where suitable conditions exist for its operation.

## DESCRIPTION OF THE INSTRUMENT

The instrument, illustrated by Fig. 1, consists primarily of a hand-operated cable reel, Esterline-Angus recorder, and amplifier. It utilizes a Western Electric thermistor (type 14B) as the temperature-sensitive element. Since the instrument was designed for use in relatively protected bodies of water, the depth is obtained by measuring the amount of paid-out cable. This is accomplished by connecting the cable reel mechanically to the paper drive on the Esterline-Angus recorder in such a manner that one turn on the cable reel, which pays out one meter of cable, moves the recorder paper one division. The instrument is designed to cover five temperature ranges: 0–50° C,

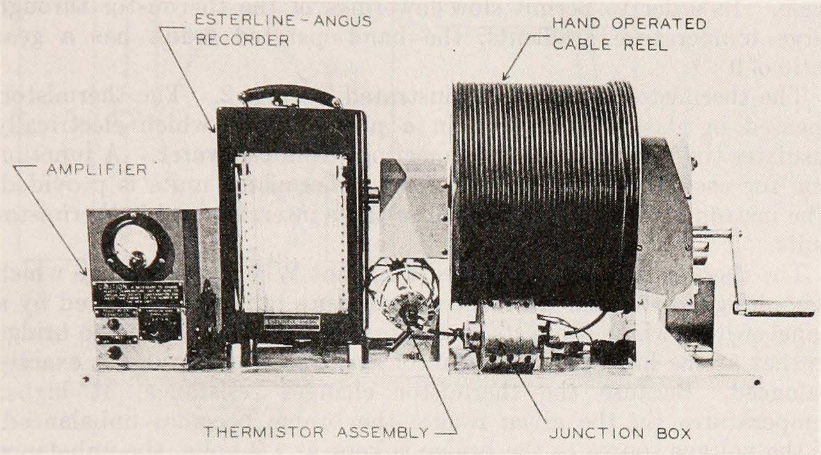

Figure 1. Temperature Profile Recorder showing the various components.

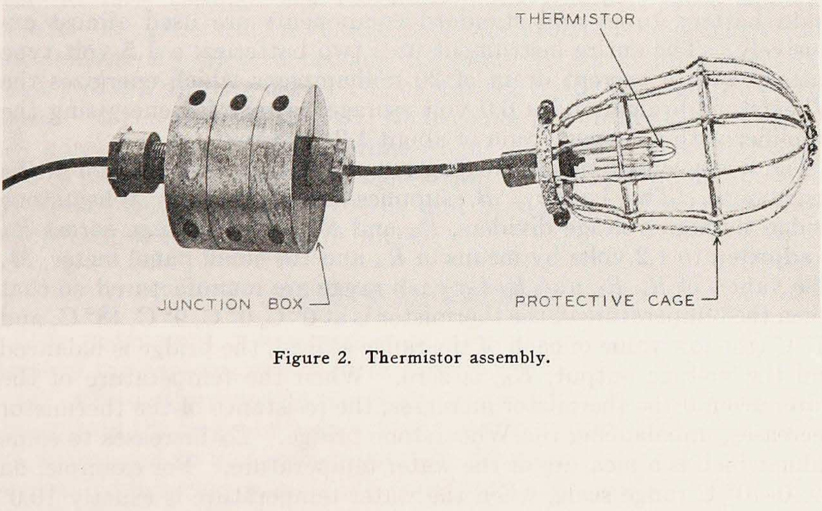

Figure 2. Thermistor assembly.

0–10° C, 9–19° C, 18–28° C, and 27–37° C, with a calibrated accuracy of ± 0.5° C on the 50° C range scale and ± 0.1° C on the 10° C range scale. In order to permit slow lowerings of the thermistor through large temperature gradients, the hand-operated crank has a gear ratio of 9 : 1.

The thermistor assembly is illustrated by Fig. 2. The thermistor, encased in glass, is mounted in a plastic block which electrically insulates the thermistor lead connections from the water. A junction box for easy replacement of damaged thermistor units is provided. The instrument is designed to utilize three interchangeable thermistor units.

The thermistor is part of a direct current Wheatstone bridge which is so designed that the different temperature ranges are selected by a panel switch, which connects special precision resistors into the bridge so that at the lowest temperature of each range the bridge is exactly balanced. Because the thermistor changes resistance, at higher temperatures (in the given range) the bridge becomes unbalanced. If the voltage source to the bridge is kept at 1.2 volts, the unbalance voltage is a measure of the temperature of the thermistor. The unbalance voltage is amplified and measured on the Esterline-Angus recorder. The bridge resistors are made of manganin wire, which allows the recorder to work in average air temperatures without affecting the accuracy of the resistors.

The instrument has been designed to give maximum performance with the least current drain and expense practicable. Low current drain battery tubes and standard components are used almost exclusively. The entire instrument uses two batteries: a 1.5 volt type battery with a current drain of 20 milliamperes which energizes the Wheatstone bridge; and a 6.0 volt storage battery for energizing the amplifier with a current drain of about 1.2 amperes.

Fig. 3 is a schematic circuit diagram of the electronic portion of the instrument. The battery, $B$, supplies power for the Wheatstone bridge through voltage dividers, $R_A$ and $R_B$. The voltage across $R_B$ is adjusted to 1.2 volts by means of $R_A$ and the small panel meter, $M$. The values of $R_1$, $R_2$, and $R_3$ for each range are manufactured so that when the temperature of the thermistor is at 0° C, 0° C, 9° C, 18° C, and 27° C (the low value of each of the range scales), the bridge is balanced and the voltage output, $E_B$, is zero. When the temperature of the water around the thermistor increases, the resistance of the thermistor decreases, unbalancing the Wheatstone bridge. $E_B$ increases to some value which is a measure of the water temperature. For example, on the 0–10° C range scale, when the water temperature is exactly 10.0° C, $E_B$ is 0.124 volt. This voltage is compared electronically with the

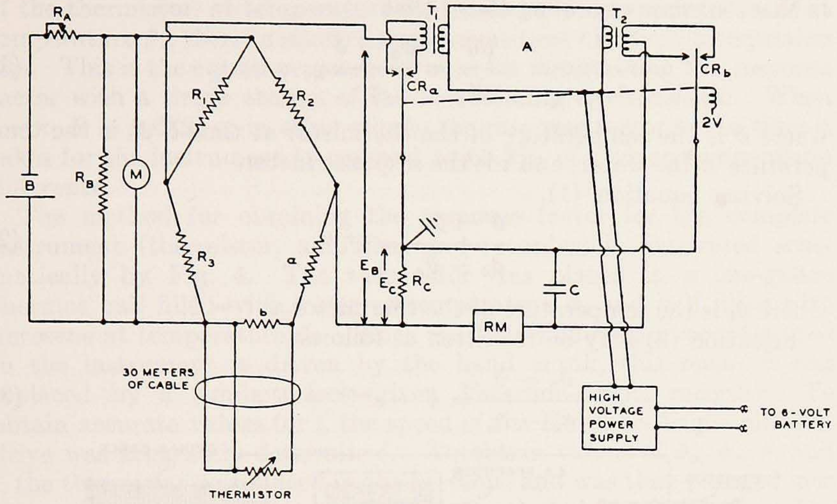

Figure 3. Schematic circuit diagram of Temperature Profile Recorder (TPR).

voltage across $R_C$, and the difference is changed to alternating current voltage by the synchronous vibrator arm, *CRa*, and amplified by the amplifier, *A*. The amplified voltage is rectified or demodulated by arm *CRb* and again becomes direct current voltage many times greater than the incoming voltage. This direct voltage causes a current to pass through the Esterline-Angus recorder, *RM*, and the resistor, $R_C$, generating a voltage $E_C$. The system is so designed that the voltage $E_C$ tries to become the same as $E_B$ at all times. (In reality it is a servo-system.) Thus, for the 0–10° C range, $R_C = 124$ ohms. When $E_B = 0.124$ volt, $E_C$ becomes practically 0.124 volt and the current through the Esterline-Angus recorder is one milliampere or full scale. The recording meter thus indicates 0 milliampere for 0° C, one milliampere for 10° C, and proportionally between those temperatures on the 0–10° C range.

## RESPONSE FACTOR

The instrument is designed to provide a continuous record of the vertical temperature profile. In order to be certain that the instrument is actually recording the *in situ* temperature, it was necessary to investigate the response factor ($\tau$) of the instrument when the thermistor is exposed to various temperature gradients. In order to obtain reasonable lowering rates of the thermistor, this response factor must be relatively small.

Newton's law of cooling states that

$$\frac{d\vartheta}{dt} = \frac{\vartheta_a - \vartheta}{\tau}\,, \tag{1}$$

where $\vartheta$ is the temperature of the thermistor at time $t$, $\vartheta_a$ is the temperature of the water, and $\tau$ is the response factor.

Solving equation (1),

$$\frac{\vartheta - \vartheta_a}{\vartheta_0 - \vartheta_a} = e^{-t/\tau}\,, \tag{2}$$

where $\vartheta_0$ is the temperature of the thermistor at $t = 0$.

Equation (2) may be rewritten as follows:

$$\frac{\vartheta_0 - \vartheta}{\vartheta_0 - \vartheta_a} = 1 - e^{-t/\tau} = R\,. \tag{3}$$

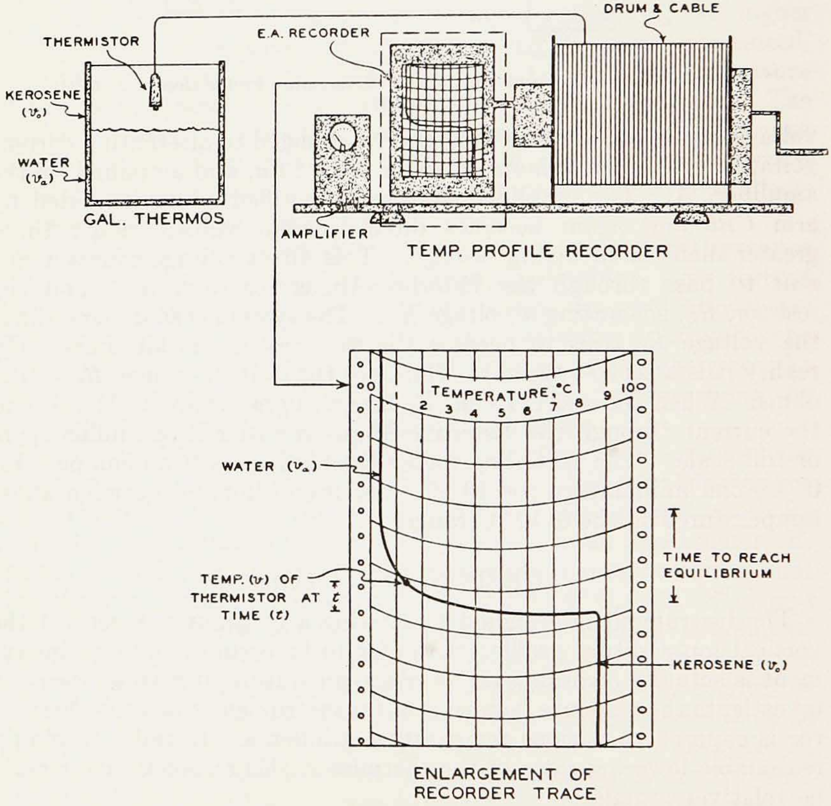

Figure 4. Schematic diagram of method used for determining response factors.

If the thermistor, at temperature $\vartheta_0$, is suddenly moved into water at temperature $\vartheta_a$, then its relative response at time $t$ is given by equation (3). This is the equation generally used for determining the response factor with a single change of the surrounding environment. When $t = \tau$, $R = 0.632$; or in other words, the response factor is the time it takes for the instrument to respond to 63.2% of a given temperature difference.

The method for obtaining the response factor for the complete instrument (thermistor, amplifier, and recorder) is illustrated schematically by Fig. 4. The thermistor was placed in a one-gallon thermos half filled with water at temperature $\vartheta_a$ and half filled with kerosene at temperature $\vartheta_0$. Since the Esterline-Angus recorder used in the instrument is driven by the hand crank, this recorder was replaced by a similar clock-driven Esterline-Angus recorder. To obtain accurate values for $t$, the speed of the Esterline-Angus recorder drive was accurately determined. To obtain values of $\vartheta_a$, $\vartheta_0$, $\vartheta$, and $t$, the thermistor was placed in the kerosene and was then plunged into the water with a resulting trace similar to that shown in Fig. 4. The response factor was then computed for the given set of conditions.

Table I summarizes the response factors for the entire instrument by utilizing three different thermistors and temperature differences ($\vartheta_0 - \vartheta_a$) varying from 0.9° C to 19.0° C. The average response factors for the system with thermistors No. 2, 3, and 11 were 1.5, 1.3, and 1.4 seconds respectively.

In order to obtain the response factor for the thermistor alone, the same method as that described above was used, except that the instrument's recorder and amplifier were replaced by a high-speed recorder and amplifier whose response factors were essentially zero.

TABLE I. SUMMARY OF RESPONSE FACTOR

| | Determination for TPR | | |
|---|---|---|---|
| *Thermistor No.* | *No. Trials* | $\vartheta_0 - \vartheta_a$ | *Average (sec.)* |
| 2 | 3 | 1.4° C | 1.5 |
| 2 | 3 | 4.4 | 1.5 |
| 2 | 3 | 9.2 | 1.4 |
| 3 | 3 | 1.1 | 1.3 |
| 3 | 3 | 3.3 | 1.3 |
| 3 | 2 | 8.8 | 1.3 |
| 11 | 3 | 0.9 | 1.6 |
| 11 | 6 | 4.9 | 1.4 |
| 11 | 6 | 8.1 | 1.3 |
| 11 | 3 | 15.3 | 1.4 |
| 11 | 3 | 19.0 | 1.3 |

Thirteen response factor determinations for the thermistor alone were made by using the method described above. These resulted in an average value of 0.8 second. Using this value for the thermistor and a value of 1.4 seconds for the complete instrument, the response factor of the amplifier and recorder system is 0.6 second.

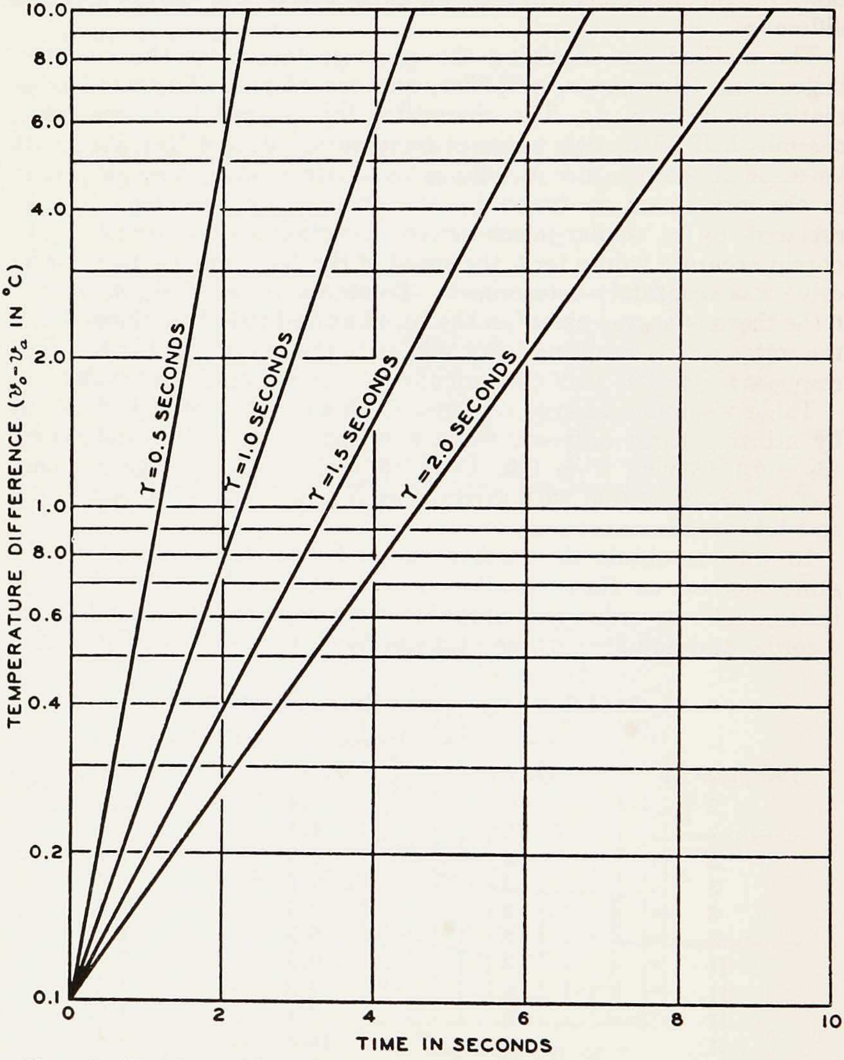

Figure 5. Time for reaching 0.1° C of a given temperature change for various response factors, $\tau$.

As previously indicated, the response factor is the time it takes for the instrument to respond to 63.2% of a given temperature change. In using this instrument for making temperature profiles, it is necessary to know the time it takes to reach within 0.1° C of any given temperature difference. Fig. 5 presents curves of this time for various response factors and temperature differences. For $\tau = 1.5$ and $\vartheta_0 - \vartheta_a = 10°$ C, approximately 6.8 seconds are required for the instrument to respond to 9.9° C of the 10.0° C temperature change. In a practical sense this means that, if a thermocline of 10.0° C is present, the thermistor must be lowered through it in not less than 6.8 seconds in order to obtain temperature with an accuracy of ± 0.1° C.

In summary, the response factor of the instrument appears to be satisfactory when used under normal or average conditions; however, if steep thermoclines are present, it may be difficult to obtain true profiles.

## CALIBRATION AND VERIFICATION OF ACCURACY

In order to obtain absolute temperatures, the instrument was calibrated against a copper-constantan thermocouple made of Leeds-Northrup thermocouple wire. This thermocouple in turn had been calibrated against a platinum-resistance thermometer which previously had been calibrated by the U. S. Bureau of Standards.

The results of this calibration for one of the thermistors are illustrated in Fig. 6. The curves are for ranges 0–50° C, 0–10° C, 9–19° C, 18–28° C, and 27–37° C. The "dots" indicate individual calibrations.

In order to be certain that the instrument will actually measure *in situ* temperatures, the instrument was compared against standard deep-sea reversing thermometers calibrated to an accuracy of ± 0.02° C. These thermometers have been used for many years by oceanographers to obtain accurate sea temperatures and their accuracy has been verified many times (Sverdrup, 1946: 347). In addition, comparisons were made against the bathythermograph (Spilhaus, 1938). Comparisons were made in sea water off the Coronado Islands, and in fresh water at Lake Hefner, a storage reservoir for Oklahoma City, Oklahoma. The thermistor, bathythermograph, and reversing thermometers were lowered in such a manner as to obtain simultaneous readings. For 23 individual comparisons with reversing thermometers, using the 10° C range scales on the TPR, the range of variation of the temperature was from − 0.1° C to + 0.2° C; 11 comparisons showed exact agreement and 10 showed a variation of ± 0.1° C. Comparisons with the bathythermograph gave a variation from − 0.3° C to + 0.2° C in 23 cases. Eighteen of the above comparisons were within a ± 0.1° C interval. From this evidence it may be concluded that the instrument has an accuracy of ± 0.1° C on the 10° C range scales.

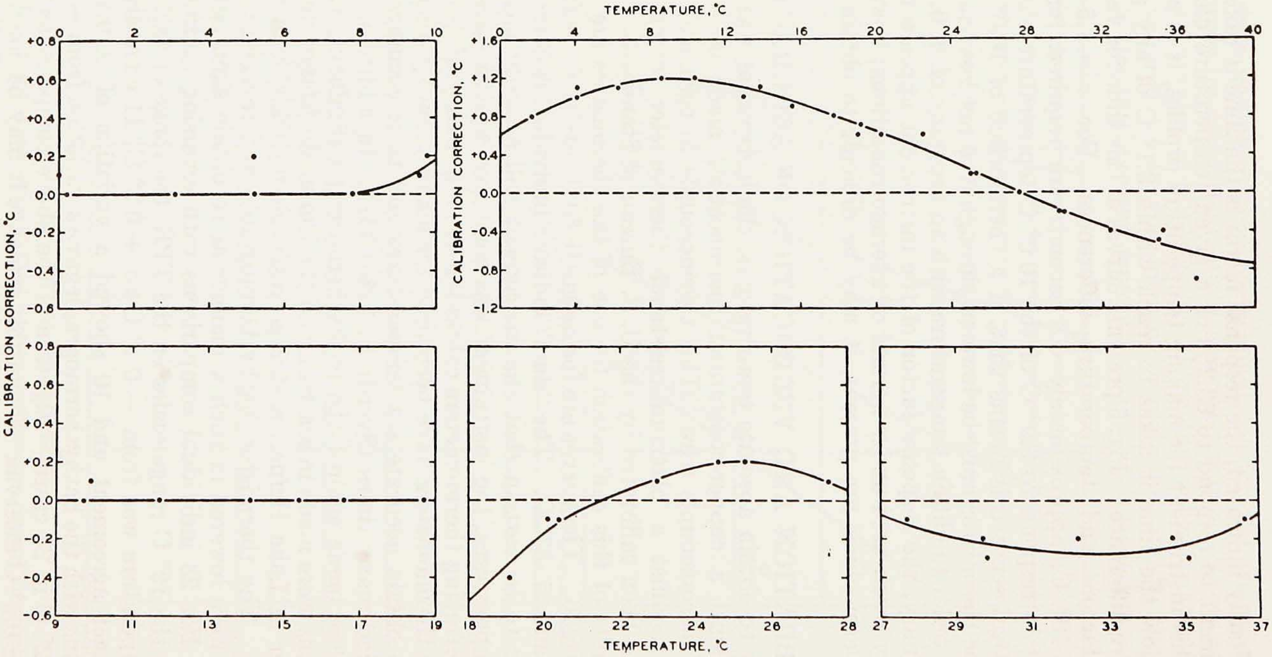

Figure 6. Calibration curves for a single thermistor.

## APPLICATION

The instrument was originally developed for use in the Lake Hefner Evaporation Studies being conducted in Oklahoma (Anderson, et al., 1950). It was necessary, in this study, to obtain temperature profiles for evaluating the energy storage term in the energy budget equation. Since the average depth of Lake Hefner is approximately 10 m, it was necessary to obtain some of the temperature profiles in water approximately 3 m in depth. It was felt that the bathythermograph, which has been utilized previously in studies of this type, would be neither accurate nor sensitive enough when used in such shallow water.

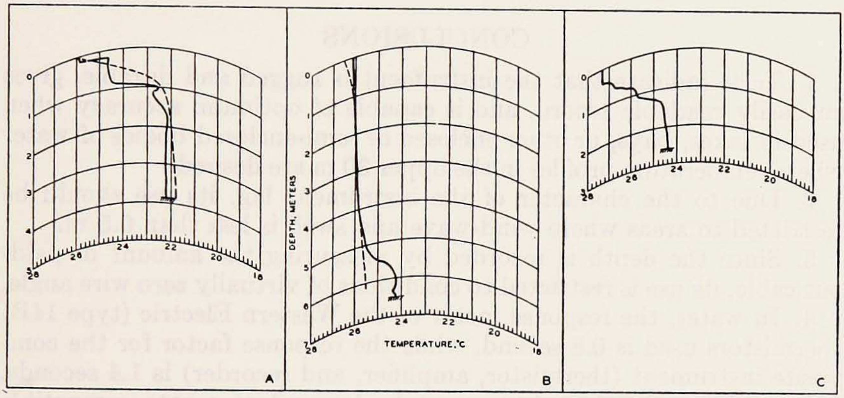

Figure 7. Temperature profiles from Lake Hefner, Oklahoma City, Oklahoma, showing comparison of a TPR (solid line) with a BT (dashed line).

Figs. 7A, B, and C illustrate some actual temperature profiles taken at Lake Hefner in shallow water. All three examples illustrate the detail that can be obtained by the instrument in depth intervals of only 1 or 2 m.

The profile illustrated by Fig. 7A was taken during an afternoon when the surface water was heated under relatively calm conditions and then wind-stirred to a depth of 0.8 m. The wind subsequently ceased and the upper 0.2 m (approximately 7 inches) was heated another 1.2° C. Fig. 7B illustrates a case where wind stirring had occurred to within a meter of the bottom and clearly shows the temperature distribution in the colder unmixed bottom water. Fig. 7C shows the step-like temperature profile present under heating conditions with wind stirring occurring intermittently.

The dashed lines on Figs. 7A and B indicate the bathythermograph taken simultaneously with the TPR profile.[1] From a study of Figs. 7A and B it is evident that the thermistor-sensitive instrument gives considerably more detail than the bathythermograph, especially in the top or bottom 1 m layer. In the case of Fig. 7C, it was not possible to obtain a useful bathythermogram, apparently due to the shallowness of the water.

## CONCLUSIONS

1. Tests indicate that the instrument is rugged and durable, gives an easily readable record, and is capable of optimum accuracy when used in lakes, bays, or other enclosed or semi-enclosed bodies of water where temperature profiles in the upper 30 m are desired.
2. Due to the character of the instrument lag, its use should be restricted to areas where wind-wave and swell is less than 0.5 m.
3. Since the depth is recorded by measuring the amount of paid-out cable, its use is restricted to conditions of virtually zero wire angle.
4. In water, the response factor of the Western Electric (type 14B) thermistors used is 0.8 second, while the response factor for the composite instrument (thermistor, amplifier, and recorder) is 1.4 seconds. In actual use the thermistor must be lowered at a rate compatible with the strength of the thermocline in order to obtain *in situ* temperatures.
5. Comparison of the instrument, under field conditions, with deep-sea reversing thermometers and bathythermographs gives an accuracy of ± 0.1 C on the 10° C range scales.

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[1] The two profiles need not coincide, since a calibration correction must be applied to the TPR temperatures to obtain *in situ* temperatures. However, the shape of the profiles should be the same, since the variation in the calibration correction is small compared to the total range of temperature.

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