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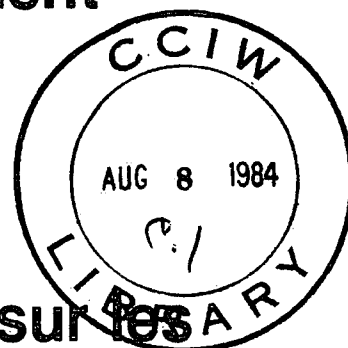


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THE DEMONSTRATION OF A CORRECTION  
TECHNIQUE TO IMPROVE SPATIAL INFORMATION  
FOR OXYGEN PROFILES

by

J.S. Ford

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**Inland Waters  
Directorate**

**Direction Générale  
des Eaux Intérieures**

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**THE DEMONSTRATION OF A CORRECTION  
TECHNIQUE TO IMPROVE SPATIAL INFORMATION  
FOR OXYGEN PROFILES**

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Hydraulics Division  
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January 1984

## ABSTRACT

Some of the spatial information in a profile is distorted or lost by the time response characteristics of the sensor. In some cases, such as an oxygen profile, the information can be restored to a limited degree that is dictated by the noise imbedded in the signal. A few profiles are processed and plotted to demonstrate the effectiveness and limitations of the correction technique.

## RÉSUMÉ

Certaines données spatiales permettant d'établir un profil sont déformées ou perdues en raison des caractéristiques relatives au temps de réponse du détecteur. Dans certains cas, par exemple l'établissement du profil de concentration d'oxygène, on peut restituer les données jusqu'à une certaine limite imposée par le bruit inclus dans le signal. Quelques profils sont traités et reproduits graphiquement pour montrer l'efficacité et les limites de la technique de correction.

## MANAGEMENT PERSPECTIVE

This report demonstrates that oxygen profiles obtained with a sensor having a characteristically slow response time may be enhanced as to accuracy by recognizing that the sensor characteristic is similar to a single-pole low-pass filter. In effect, the technique "de-filters" the recorded oxygen signal. The benefit of the technique is either that a more accurate interpretation may be made of a given oxygen profile record, or that given data accuracy specifications may be attained with higher speed profiles, with consequent savings in time or station. Most importantly, the technique broadens the method of analysis and interpretation of oxygen profile records, and hence increases their value by enhancing the information contained in them.

T. Milne Dick  
Chief  
Hydraulics Division

NOTE: Mention of a commercial product does not imply endorsement of that product or rejection of others for the intended purpose.

## PERSPECTIVE DE GESTION

Le présent rapport montre qu'il est possible d'améliorer la justesse des profils de concentration d'oxygène obtenus avec un détecteur dont le temps de réponse est lent, si on considère que la caractéristique du détecteur est semblable à un filtre passe-bas unipolaire. En effet, cette technique "défiltre" le signal correspondant à la concentration d'oxygène. Elle présente l'avantage d'établir une interprétation plus juste d'un profil de concentration d'oxygène ou d'obtenir des spécifications sur la justesse des données avec une vitesse d'enregistrement plus élevée, ce qui permet de sauver du temps ou de ne pas avoir à utiliser une autre station. De plus, la technique élargit la méthode d'analyse et d'interprétation des profils de concentration d'oxygène et augmente donc leur valeur puisque les données sont plus précises.

T. Milne Dick

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## 1.0 INTRODUCTION

When a membraned oxygen sensor is being lowered through the water to produce a profile of a stratified lake and the response time of the sensor is slower than the time rate of change of the oxygen content, the record of the oxygen concentration is in error. Usually the features are displaced and distorted.

Through a simple correction technique, the signal can be restored somewhat providing the sensor behaves similarly to a single-pole low-pass filter. However the correction technique also enhances the noise introduced from electronic circuits and turbulent water. Therefore some of the restoration of the high frequency signals must be sacrificed by signal averaging to keep the noise within limits. A balance must be achieved between the noise to be rejected and the high frequency information to be retained in the final profile.

Examples are given showing the effects of prefiltering on the corrected profile. As well a sample of profiles is given to show the good and adverse effects of the correction technique. There are optimum speeds to profile which depend upon whether high throughput of data or high accuracy of the data are required.

Figure 1 shows the system that makes use of an oxygen sensor that has quite a slow response. The data from the profile are restored through a program used on the microcomputer.

## 2.0 THEORY

Correction techniques have been applied for many years on data from frequency limited sensors. The problem is more difficult when more than one sensor is required to obtain the final readings, for example, ocean salinity profiles (Horne and Tode, 1980).

Some major simplifications can be made in the case of an oxygen sensor because the speed of response is much less than that of the temperature and pressure sensors. This allows the oxygen sensor data to be treated with a single time response correction equation as described by Fofonoff et al. (1974) and Ford (1982). It restores much of the spatial information that was lost or distorted by the slow responses of the oxygen sensor.

The corrected value at a time,  $t$ , for a sensor having a single-pole, low-pass response is:

$$y_o(t) = y(t) + \tau \frac{dy}{dt}$$

where  $y(t)$  is the uncorrected signal from the sensor as a function of time

$\tau$  is the time constant of the sensor

$\frac{dy}{dt}$  is the rate of change of the uncorrected signal from the sensor.

Four imperfections influence the application of this equation. The data are samples rather than continuous; the data are contaminated with noise; the time constant is a variable with temperature and possibly pressure; and the sensor's response is only an approximation to a single-pole, low-pass response.

The noise effects can be minimized by digital filtering techniques. For a sequence of discrete voltage signal readings that contain redundant information but randomly varying noise, the estimate  $(V_1 + V_2) / 2$  is usually better than  $V_1$  or  $V_2$  in determining the true value of the signal. However, if this averaging process is continued over increasing numbers of samples, the redundancy may be insufficient to the extent that detailed information is eliminated along with the noise. This is equivalent to applying an excessive low-pass filter to the signal. An optimum filter must be chosen for the application where the noise suppression and high frequency response restoration are kept in balance.

Since  $\tau$  is large in the case of the oxygen sensor, the more important filtering has to do with the rate of change of the signal rather than the signal itself. The unfiltered estimate of  $dy/dt$  is represented by a rate of change of voltage  $dV/dt$  where

$$\frac{V_1 - V_2}{\Delta t} \approx dV/dt \quad (2)$$

where  $V_1$  and  $V_2$  are consecutive voltages, volts,  
 $\Delta t$  is the time interval between samples, seconds and  
 $\frac{dV}{dt}$  is the true rate of change of the signal, volts/second

The filtering is applied by averaging the differences such as,

$$\frac{(V_1 - V_2) + (V_2 - V_3) + (V_3 - V_4)}{3\Delta t} = \frac{(V_1 - V_4)}{3\Delta t} \approx \frac{dV}{dt} \quad (3)$$

or

$$\frac{V_1 + V_2 - V_3 - V_4}{4\Delta t} \approx \frac{dV}{dt} \quad (4)$$

or

$$\frac{V_1 + V_2 + V_3 - V_4 - V_5 - V_6}{9\Delta t} \approx \frac{dV}{dt} \quad (5)$$

The filter in equation 4 is better than that in equation 3 because, for a given span of samples, all samples are used in estimating the rate of rise. For a single, spurious, offset reading for  $V$ , the filter in equation 4 gives a 25% better peak-to-peak perturbation suppression as the spurious signal passes through the process of estimating  $dV/dt$ . In the filtering process,  $V_1$  becomes  $V_2$  and so on as each new estimate arrives in the time  $\Delta t$ . This is why the perturbation is more persistent yet not as severe in the filtered case compared to the unfiltered case. The filter in equation 5 is better yet in suppressing noise because it averages more samples but there is a useful limit as mentioned earlier.

The discrete (digital) filter does not respond to step or ramp functions in the same way as an analog filter. It is useful to compare the responses to a ramp function for both filters to obtain an estimate of the low-pass contribution of the digital filter. Figure 2 shows a family of response curves for single-pole, analog, low-pass filters and responses for digital filters having different averaging schemes. For example, equation 4 describes a "two-pair" filter, because the estimate for the slope is made from two data pairs. Equation 5 describes a three-pair filter. It can be seen that for a sudden unit ramp input (the slope changes from zero to one volt per second at  $t = 0$ ) the analog and digital filters' responses are different, however, they may be grouped to give a sense of the classical time constant. For a signal sampling rate of one per second, the digital filters may be described as having a "time constant" in seconds equal to the number of pairs of data used to estimate the slope. Doubling the sampling rate to two samples per second, halves the "time constant". A similar response is seen for a three-pair filter sampling once per second as a six-pair filter sampling twice per second. The more pairs involved, the better the noise filtering, therefore the sampling rate should be as high as practical for the data gathering system.

The dependence of  $\tau$  on temperature is well behaved in some sensors so it can be described in a simple function and used in the

correction computations. The dependence of  $\tau$  on pressure is questioned at this stage and if it exists, it would be a second order correction. It is ignored in this report.

Actually the oxygen sensor exhibits a complex time response which may be described as a function of multiple exponential responses, however for most purposes, a single exponential response may be assumed providing a delay factor is added for the time it takes for the oxygen to migrate through the membrane to the electrolyte. This delay is described by Hitchman (1978) and modelled by Myland and Oldham (1981). The delay is easily compensated in the correction equation by advancing the oxygen data several sample intervals ahead of the temperature data.

The equation for corrected data points for a time-series data list is

$$W_N = V_{N+3} + (V_{N+7} + V_{N+6} + V_{N+5} + V_{N+4} - V_{N+3} - V_{N+2} - V_{N+1} - V_N)(\tau/16\Delta t). \quad (6)$$

where  $W_N$  is the corrected signal for the nth sample, mg/L  
 $V_{N+3}$  is the uncorrected signal three samples later, mg/L  
 $\tau$  is the time constant of the sensor, s  
 $\Delta t$  is the sampling interval, s.

This describes a four-pair digital filter that advances the signal by seven sample periods.

### 3.0 LABORATORY PREPARATIONS

The oxygen and temperature instruments used for profiling are thoroughly calibrated in the laboratory for offset, sensitivity and time response. To obtain the offset and sensitivity coefficients, baths of known oxygen concentration and temperature are used to produce data from the sensor. The calibration coefficients are derived by linear regression analysis. The coefficients are used to produce the values of  $V_1$  to  $V_N$ .

$V_1$  to  $V_N$  are the oxygen readings for the profile in mg/L. Temperature is treated similarly.

The time response characteristics are measured in the laboratory from step-function tests. The temperature instrument is sufficiently fast not to require correction. Its time constant (63%) is 0.17 seconds which is between 35 to 106 times faster than the oxygen probe, depending on the probe's membrane thickness and temperature. The oxygen probe's time response is determined by plunging the probe from a bath of one oxygen concentration to a bath of different concentration. Both baths are at the same temperature. The sensor being used is a Yellow Springs Instruments, Model 5739, which has a temperature compensation network incorporated to convert the readings of partial pressure of oxygen to the absolute concentration of oxygen. This network is sufficiently well matched to the sensor's time response that the remaining mismatch can be treated as short term noise superimposed on the signal. Therefore compensation for step responses between water of different temperatures are not necessary for the present level of accuracy required. However, if further refinement in the correction technique is to be applied, the remaining mismatch will have to be compensated or eliminated.

Figure 3 is an example of a step up response at 15°C. The initial transients are caused at the moment of transferring from one standard bath to another. The delay and quasi-exponential response are clear. Figure 4 is a plot of the digitized data for a step down at 5°C. The regression curve for an exponential function is superimposed on the data. From this, the inverse of the coefficient of  $t$  is taken as the time constant of the probe. Similar regressions for step up and step down at 15°C and 25°C were computed. The results are shown in Figure 5. Two functions for the step-up and step-down time constants versus temperature are evident but for simplicity a single function is used which matches the line superimposed on the points.

Temperature effects on the delay time are present but not significant enough to require a special function. The measurements of

six delays ranged from 2.8 sec. to 5 sec. over a range of 5 to 25°C. A trend was noticeable but not well defined. Further work may be required if higher accuracies in the corrected data are required. In this report the mean of the delays was used in the corrections. This amounts to seven sampling periods (3.5 seconds).

Having the time constant as a function of temperature and mean delay time, the data may be corrected with a computer program.

#### 4.0 RESULTS AND COMMENTARY

Three profiles were selected for demonstrating the application of the correction technique. One had a very sharp oxygen and temperature shift, one had an interesting and complex oxygen profile and one was a particularly bad profile taken on a stormy day where the ship's roll interfered with the downward motion of the sonde.

Figures 6, 7 and 8 show the computer printout of the whole profile without the correction process for the three cases respectively.

For the first case four correction schemes were used. These were the application of one-pair, two-pair, three-pair and four-pair filters in computing the rate of change in the oxygen signals. Figures 9, 10, 11, and 12 respectively show the effects of increasing the averaging process. The use of four pairs was adopted to provide the smoothest data without increasing the overall "time constant" beyond two seconds. This gives a factor of 3 improvement in the speed of response for water temperature of 25°C and an increase of 9 for temperatures near 0°C.

Figures 13 and 14 show the poor and complex profiles respectively after the four-pair filtering and correction have been applied. Some of the benefits and drawbacks of the correction technique may be seen in the complex and poor profile. In Figure 14, at the 48 metre mark, a distinct bulge in the oxygen line is evident. Close examination of the printed data showed that these were two readings that

were higher than the trend by less than 0.6% of full scale. These caused the correction equation to increase the offset to 4% of the reading. Whether this is a noise event or an actual oxygen feature is unknown. Similarly this question applies to the readings at the 26 metre mark.

One drawback can be seen in the corrected, poor profile (Figure 13) where overshoot is evident in six points at the 18 metre mark. This suggests that the time constant measured in the laboratory may not be correct at depth. The more likely cause is the transients coming from the probes's own temperature compensating network. The fact that the profile appears noisier than the original is not a drawback because this is actually what the oxygen and temperature sensor experienced as they were plunged up and down through the thermocline.

One benefit seen in the complex profile (Figure 14) is the restoration of the peaks of the swings in the oxygen readings around the 35 metre mark. The difference between the corrected and uncorrected peak-to-peak swings is about 0.5 mg/L dissolved oxygen.

Another benefit can be seen in comparing Figure 7 with Figure 14. At the 42 metre mark, the sonde was accelerated from 5 centimetres per second to 40 centimetres per second. The event placed a transient on the temperature data. The transient is not seen in the oxygen data until it is corrected. It is possible that the transient is caused by the sudden flushing of the sonde's cage which had been dragging water down with itself at the lower speed. This effect has been demonstrated by McCullough and Graeper (1979), and can be seen on page 76 of their report.

Figure 12 when compared to Figure 6, clearly shows the benefit of the correction where the spatial event is a sharp ramp and the profile was done smoothly. The bottom of the ramp is restored from 20.5 metres to 20.0 metres and the oxygen reading at the 20 metre depth is restored from 5 mg/L to 2.5 mg/L. This is more evident when comparing Figures 15 and 16. It is significant that these profiles were done as slowly as 5 cm per second to minimize such errors. At the 20.5

metre mark the profiling was stopped for operational reasons. In the uncorrected case, the readings caught up to the actual value as the boat jiggled the sonde about 25 cm. In the corrected profile, the "catching up" was already complete and the profile is considerably less noisy at that depth.

## 5.0 CONCLUSIONS

The simple compensation technique just described has beneficial effects on time series data such as a profile made with an oxygen sensor. This is because the YSI oxygen sensor can be treated as a single-pole, low-pass filter with a delay function and is therefore easily corrected. Since the correction technique magnifies noise that is introduced into the signal by turbulence or electronics, digital filtering of the data is necessary. This sacrifices some of the highly detailed information in the data. The filtering can also introduce anomalous series of readings if the noise produces a large anomalous reading.

The technique is beneficial when applied to the data for profiles taken even at very slow speeds (5 centimetres per second). The accuracy of the representation of the spatial features is improved. If applied to data from profiles taken at higher speeds, the same improvement applies. In highly turbulent situations, the corrected profile may not appear improved because the low-pass characteristic of the sensor tends to smooth the data. None-the-less the uncorrected profile is not better because its spatial features are displaced downward and the gradients are altered.

The ability to take profiles at higher speeds without losing the detail that would be seen in a lower speed profile has the major benefit of minimizing the time spent by the ship on each station. The speed up can be 3 to 9-fold depending upon the water temperature.

Further refinements can be made to the correction technique with respect to the transients caused by the temperature compensating

network of the oxygen sensor and the changes in the delay times with temperature. Such refinement should be done if the limitations of the present technique are known to be a problem.

#### **ACKNOWLEDGEMENTS**

Mr. Murray Charlton generously provided the profiles that were used in testing and demonstrating the correction technique. He was also instrumental in having the resources made available to do this work.

Ken Mollon produced the excellent calibration data that was used to determine the static and step response characteristics of the probe. His contributions include the development of the techniques to make the calibrations.

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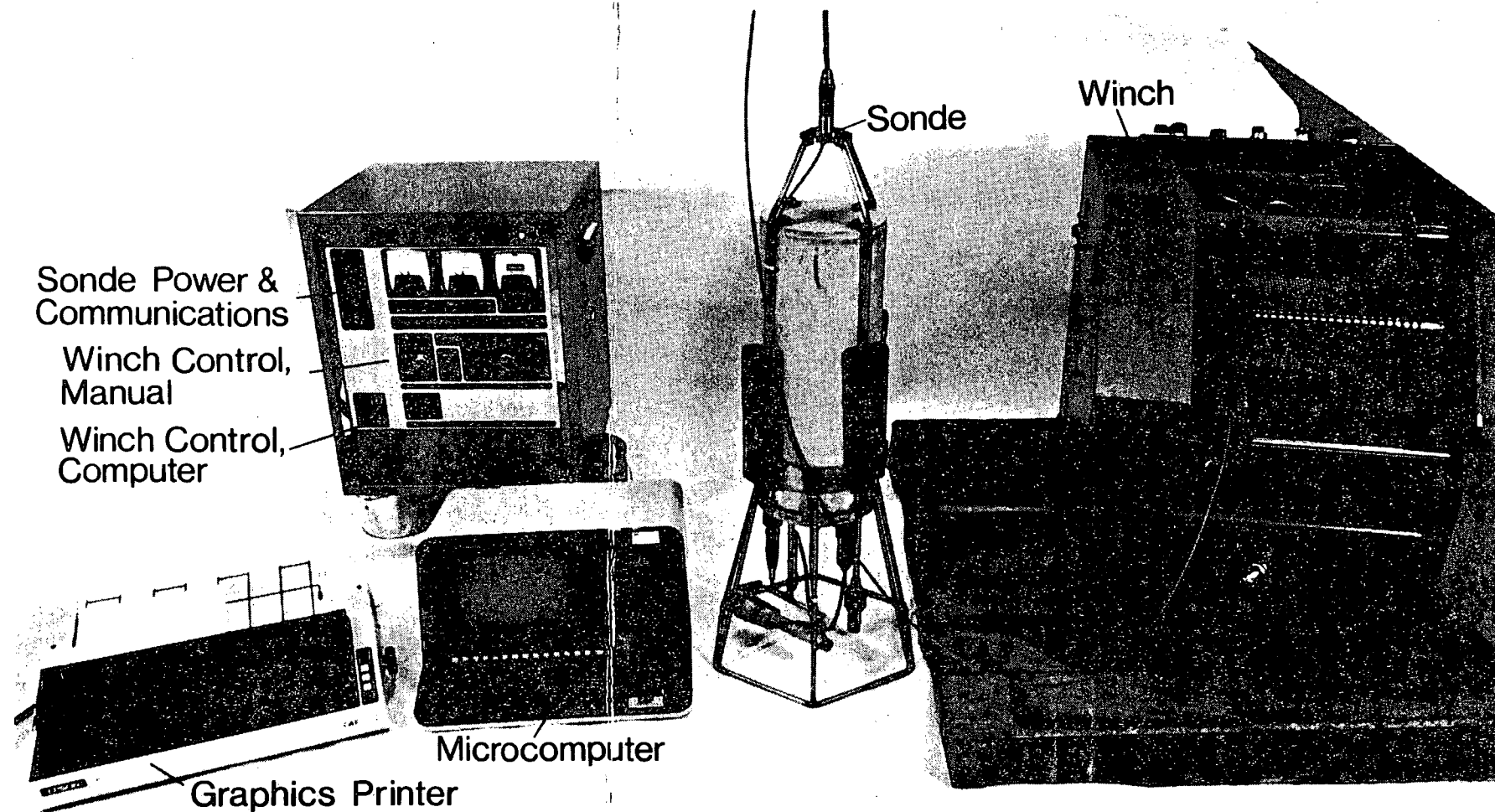


FIGURE 1. DIGITAL OXYGEN PROFILER

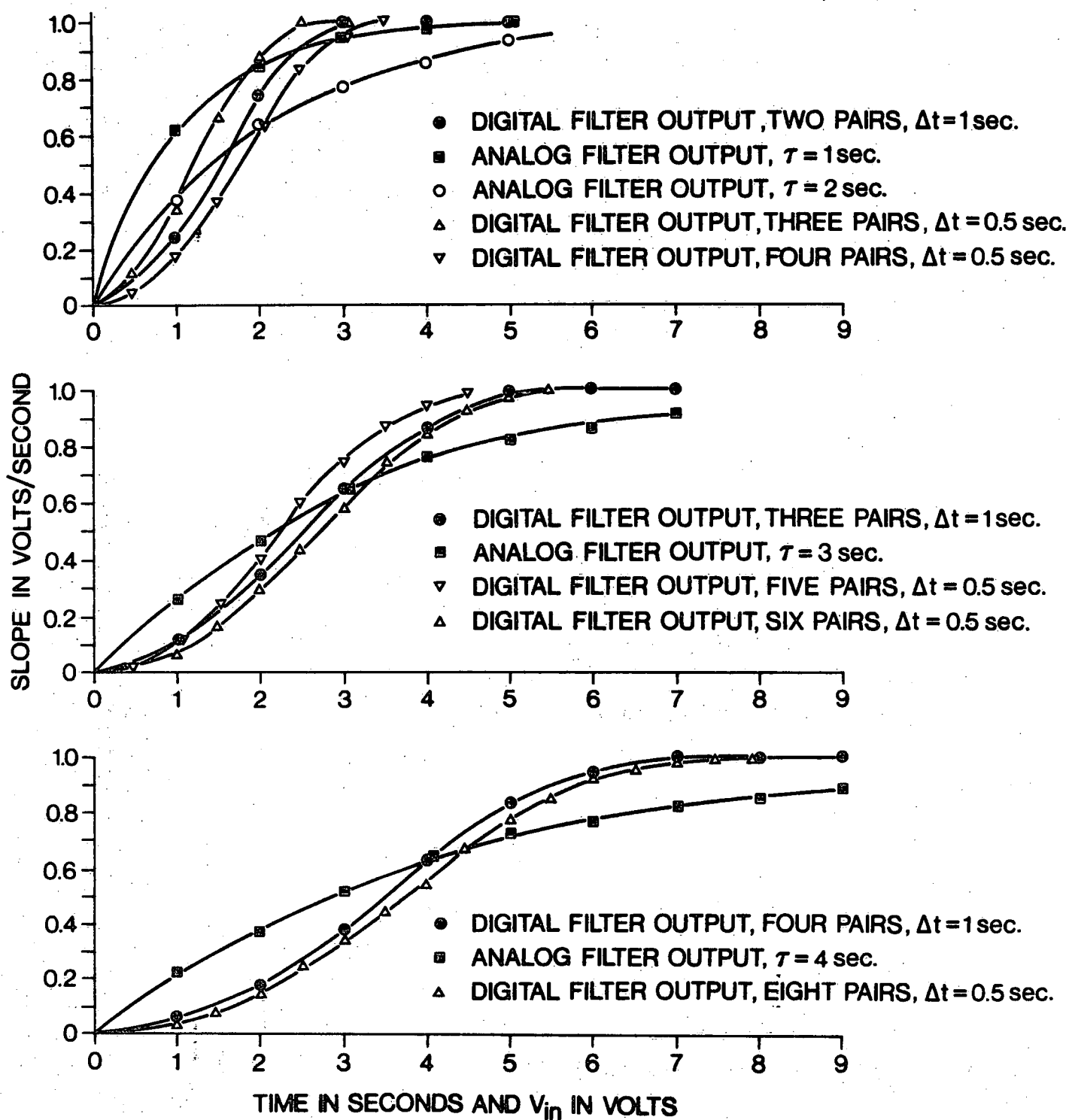


FIGURE 2. GRAPH OF DIGITAL AND ANALOG FILTER RESPONSES TO A UNIT RAMP INPUT SIGNAL

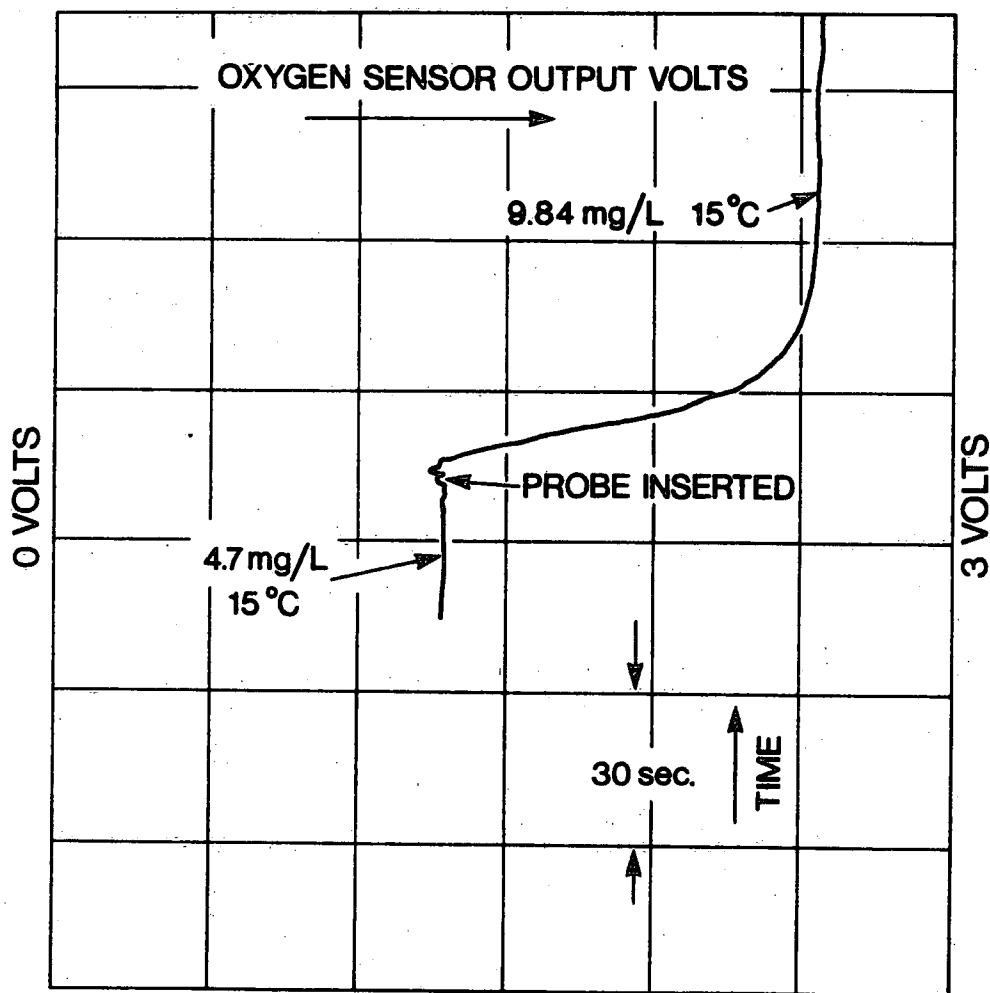


FIGURE 3. STEP RESPONSE FOR A LOW TO HIGH D.O. CONCENTRATION

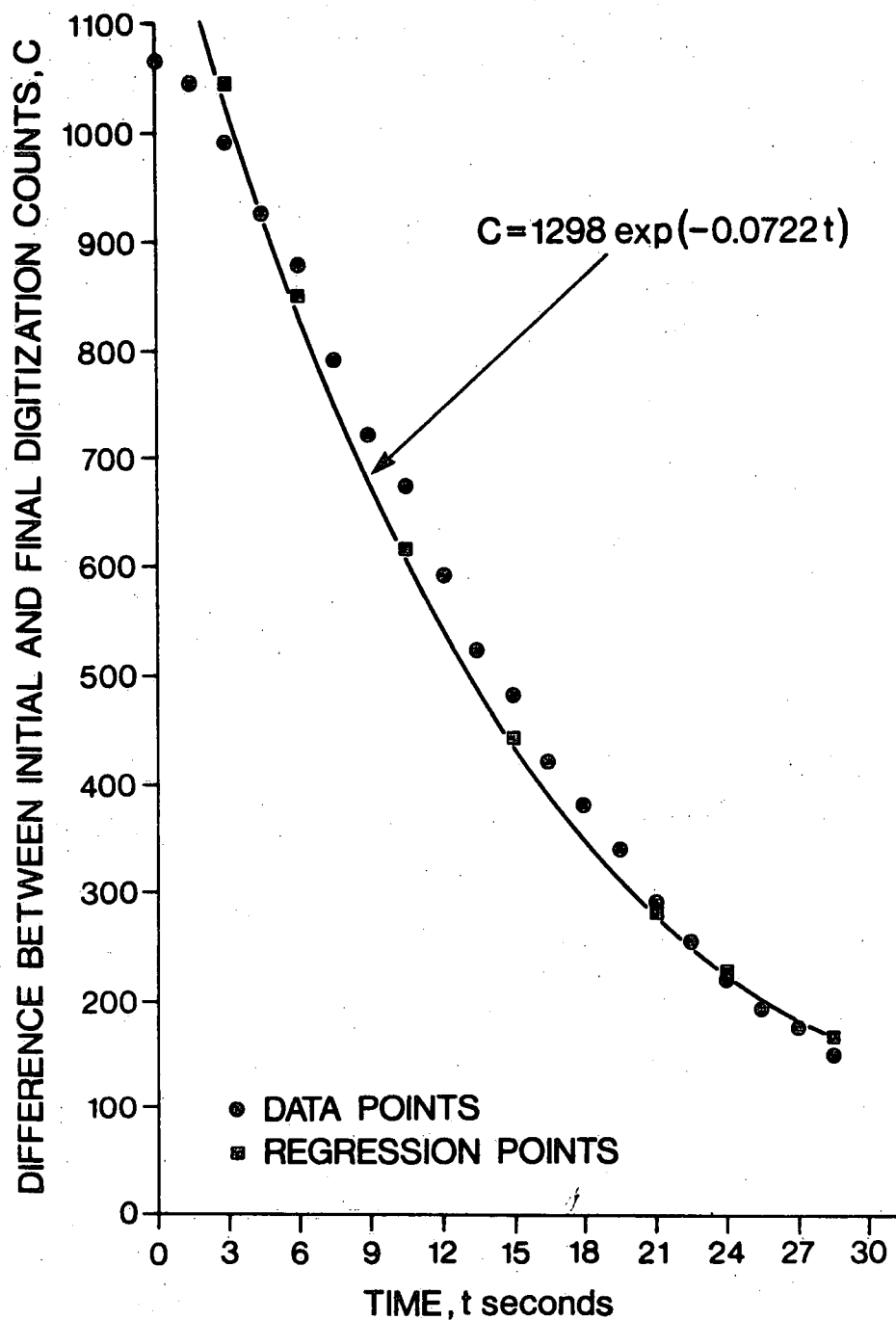


FIGURE 4. GRAPH OF DATA POINTS AND REGRESSION CURVE FOR THE TIME SERIES RESPONSE OF AN OXYGEN PROBE TO A STEP FUNCTION IN OXYGEN CONCENTRATION (at 5°C, high to low step)

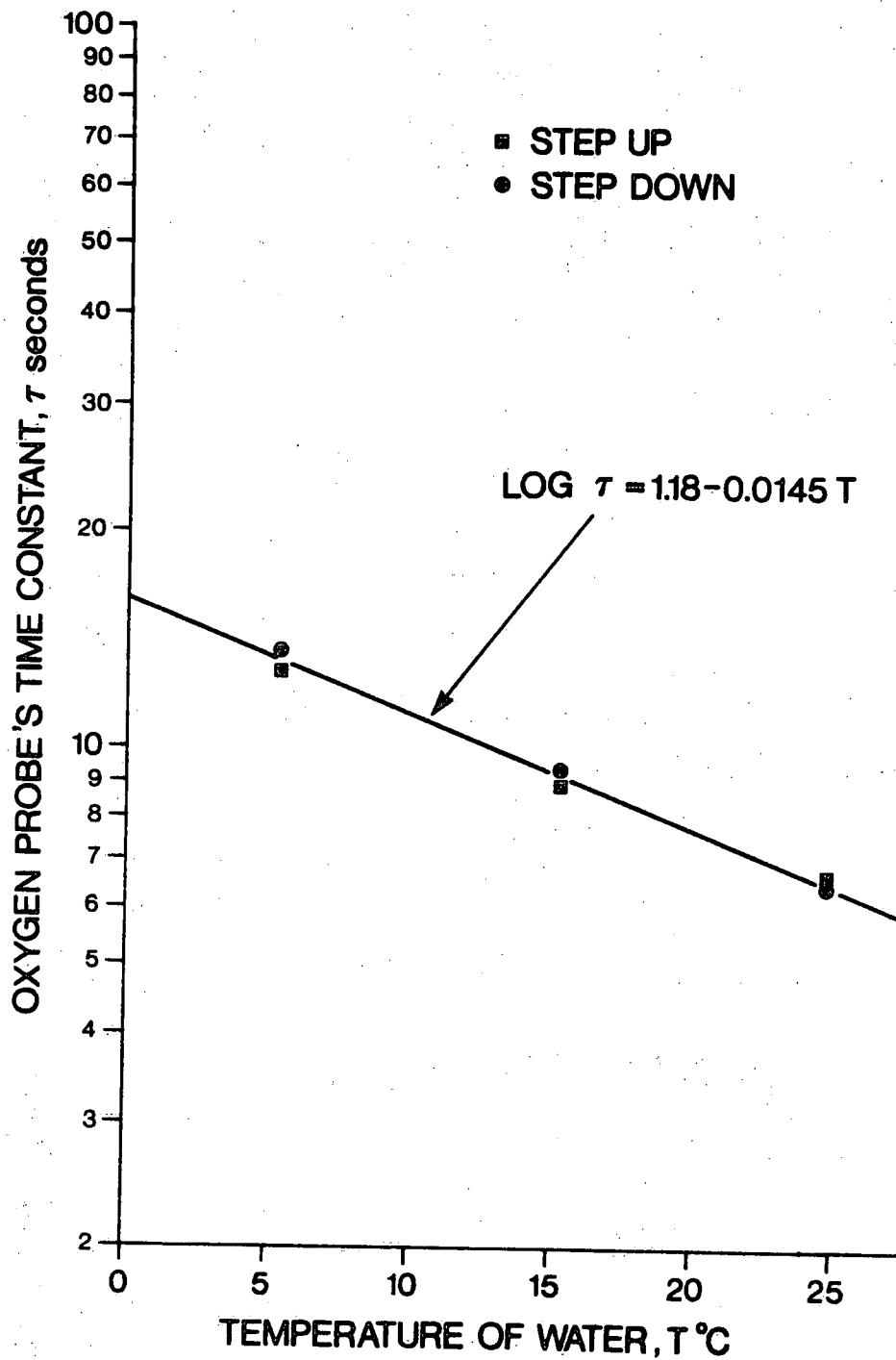


FIGURE 5. PLOT OF THE TIME CONSTANTS FOR STEP RESPONSES OF AN OXYGEN PROBE AT DIFFERENT WATER TEMPERATURES

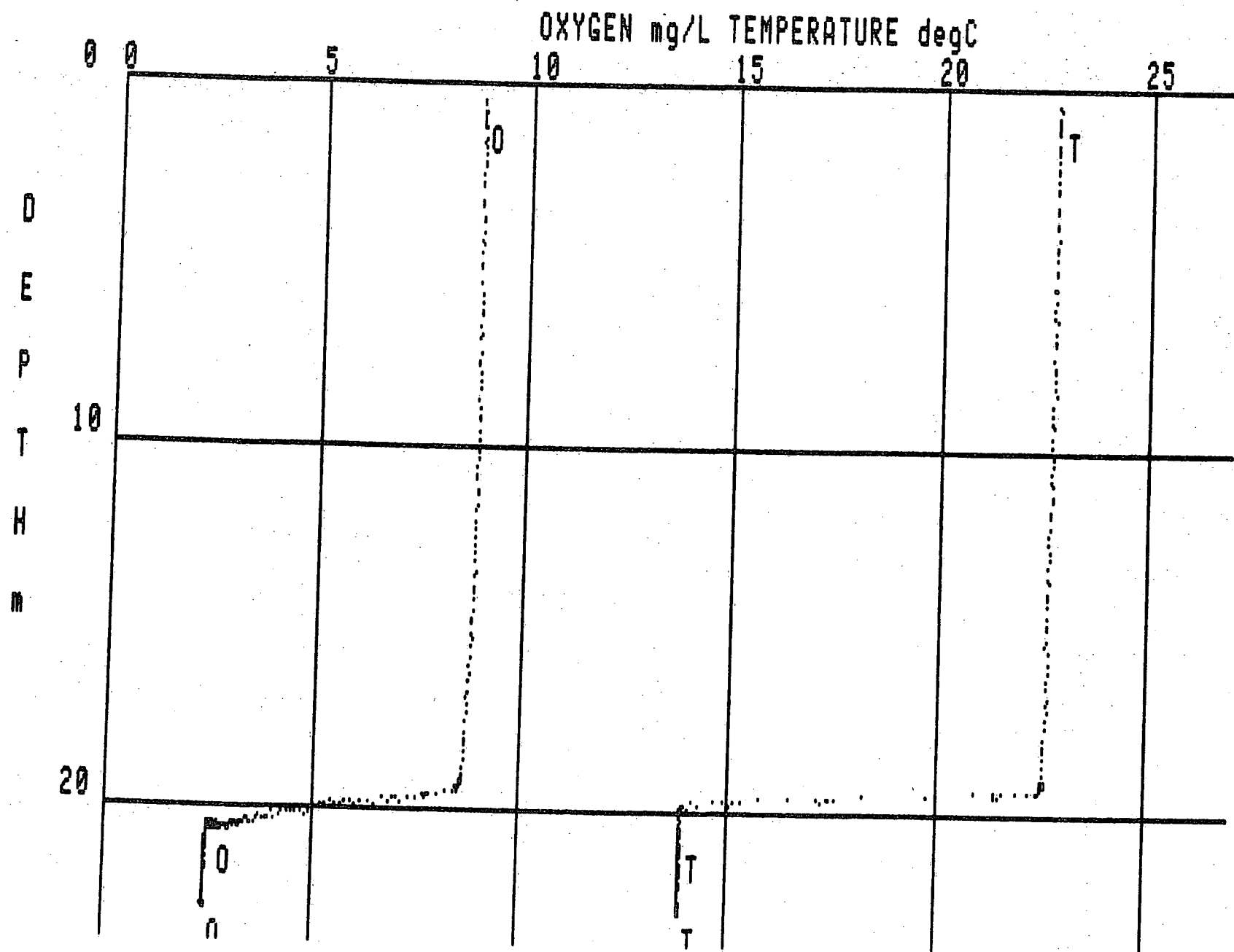


FIGURE 6. SHARP TRANSITION PROFILE - UNCORRECTED

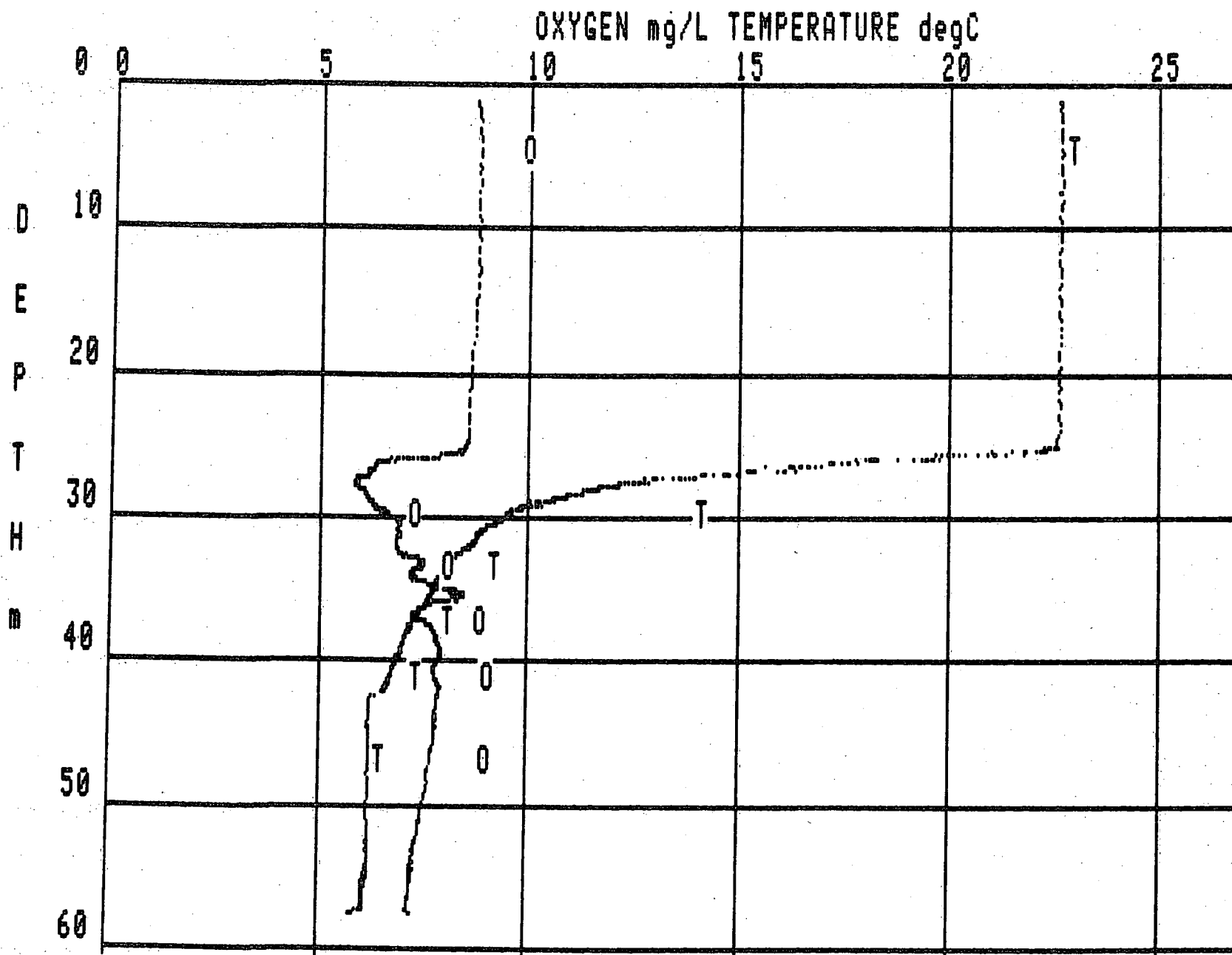


FIGURE 7. COMPLEX PROFILE - UNCORRECTED

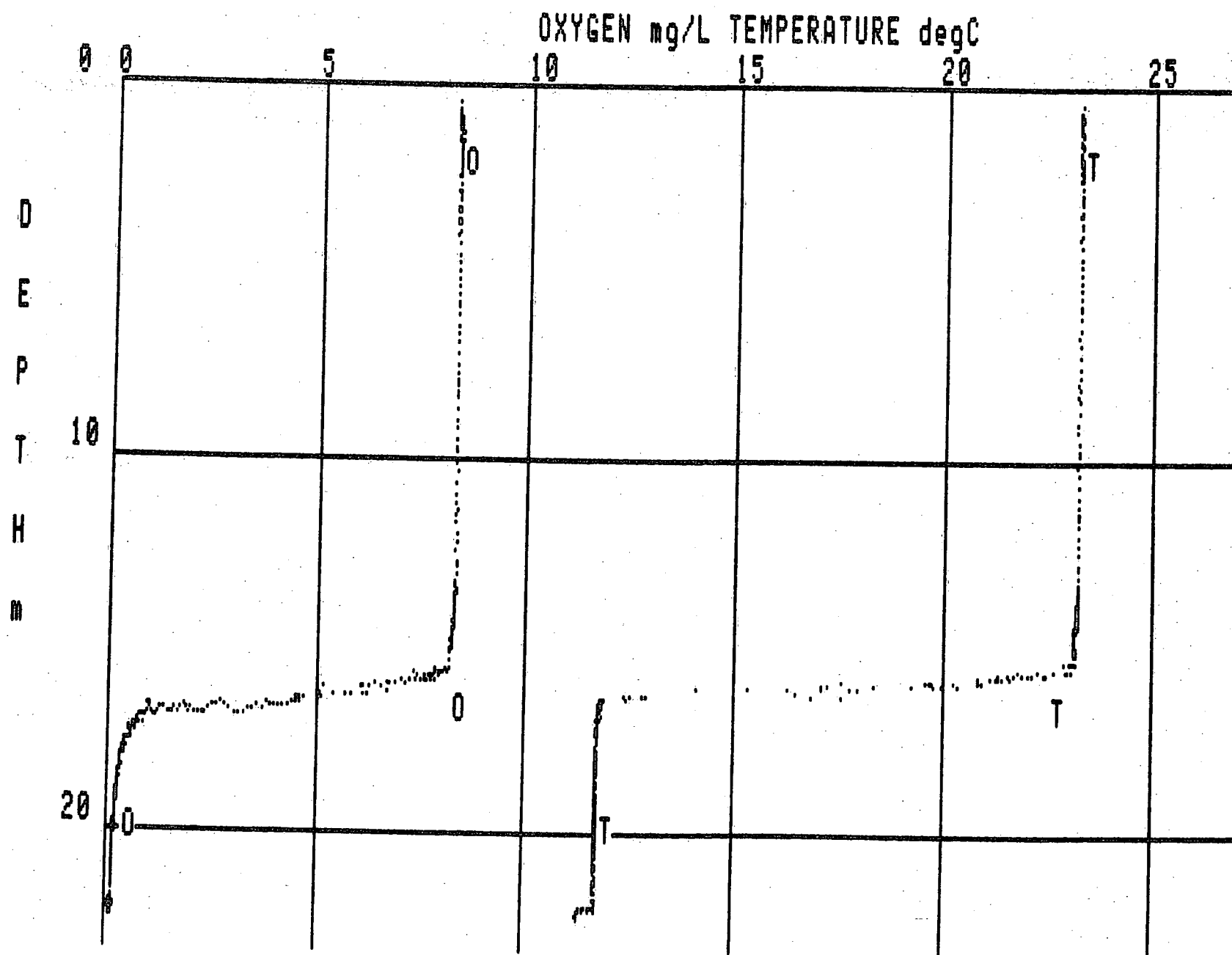


FIGURE 8. POOR PROFILE - UNCORRECTED

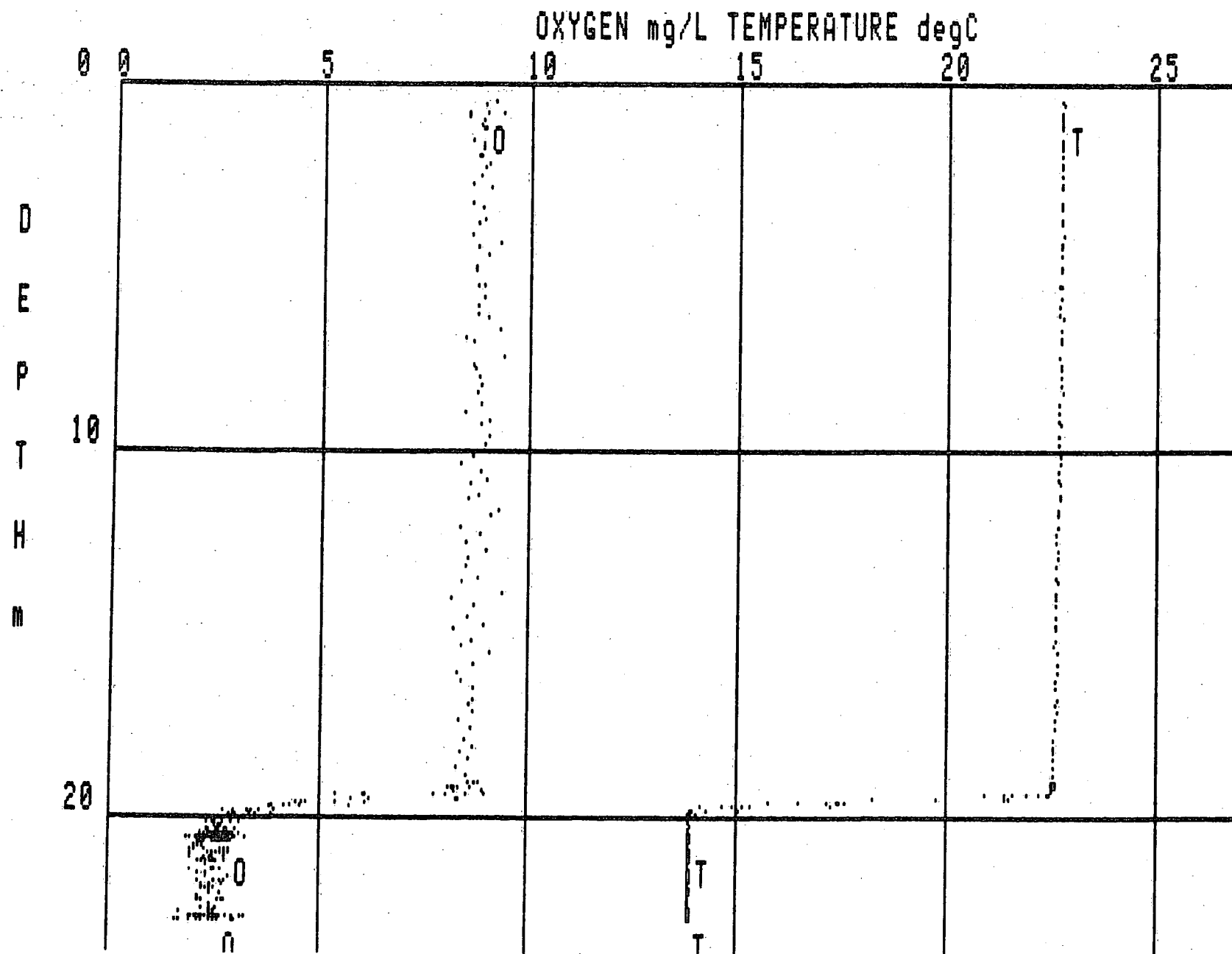


FIGURE 9. SHARP TRANSITION PROFILE - CORRECTED WITH  
NO FILTERING

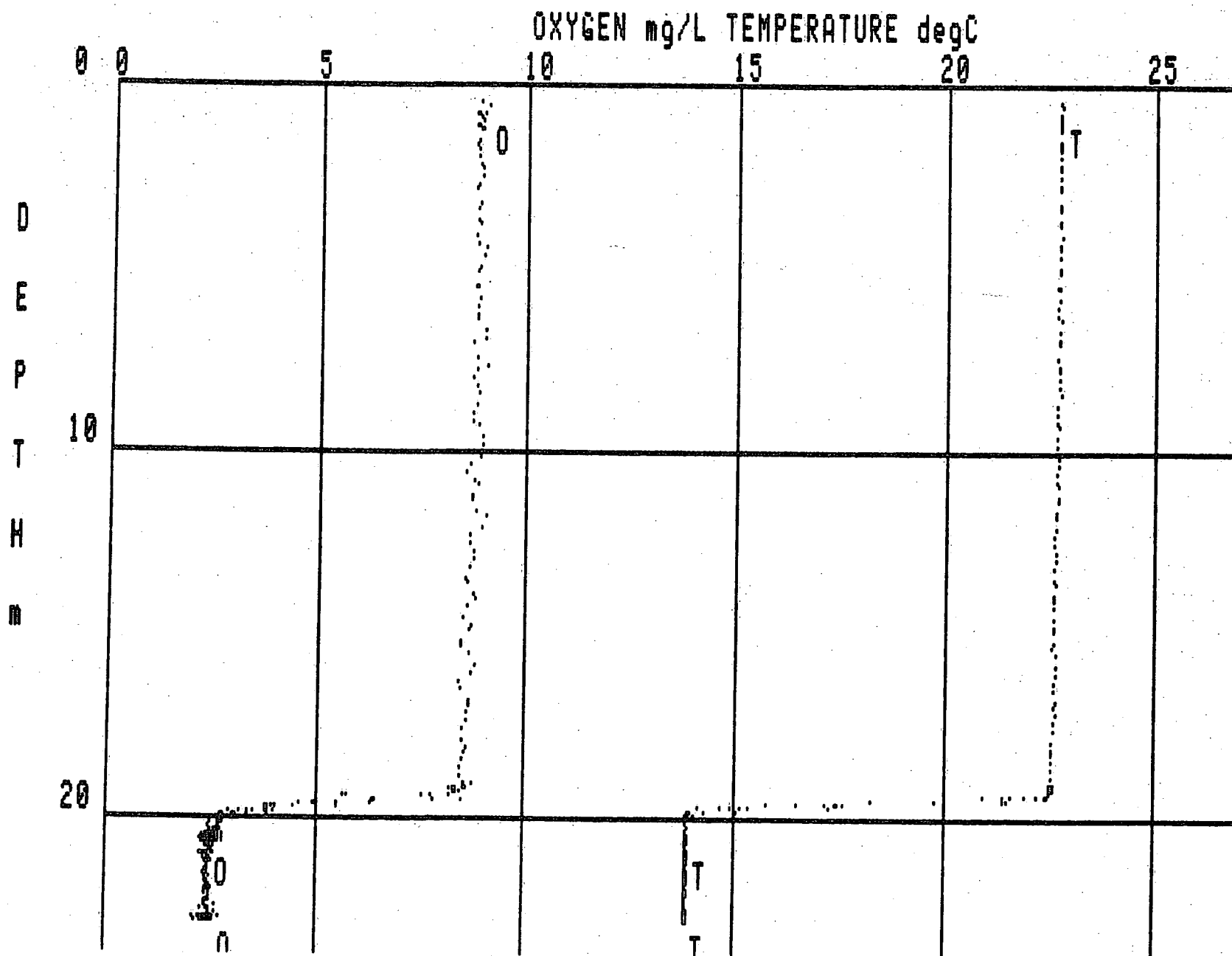


FIGURE 10: SHARP TRANSITION PROFILE - CORRECTED WITH TWO-PAIR FILTER

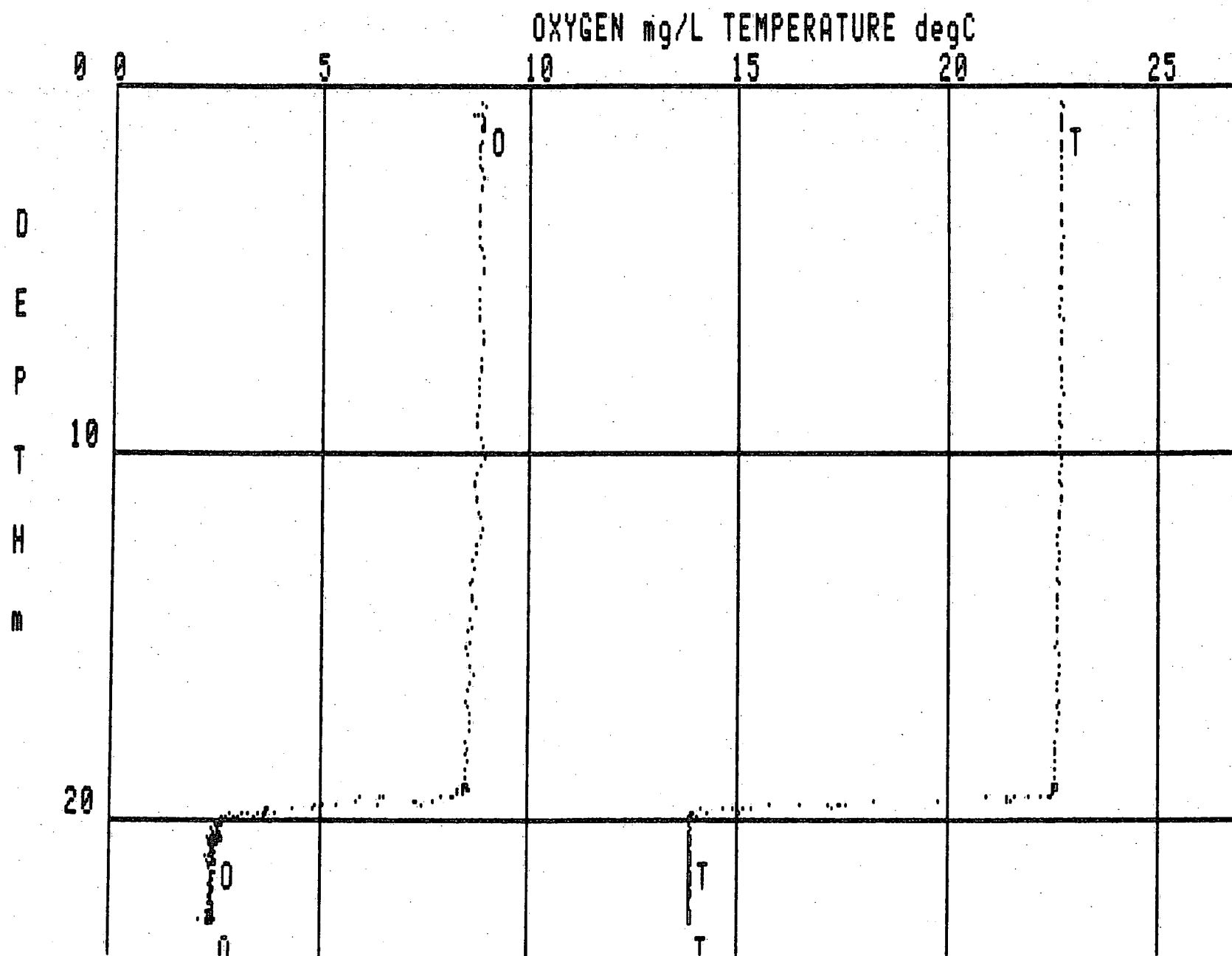


FIGURE 11. SHARP TRANSITION PROFILE-CORRECTED WITH  
THREE-PAIR FILTER

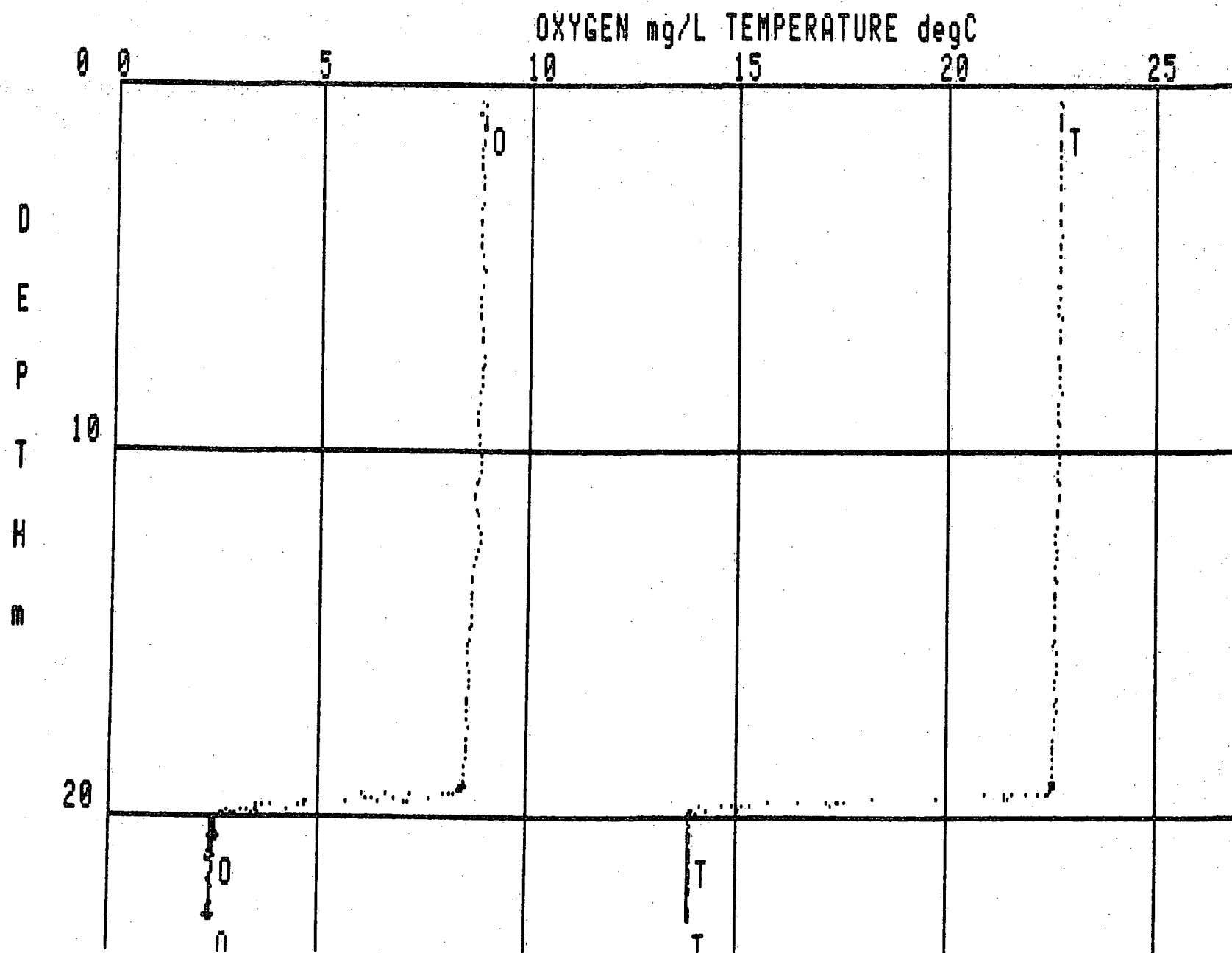


FIGURE 12. SHARP TRANSITION PROFILE-CORRECTED WITH  
FOUR-PAIR FILTER

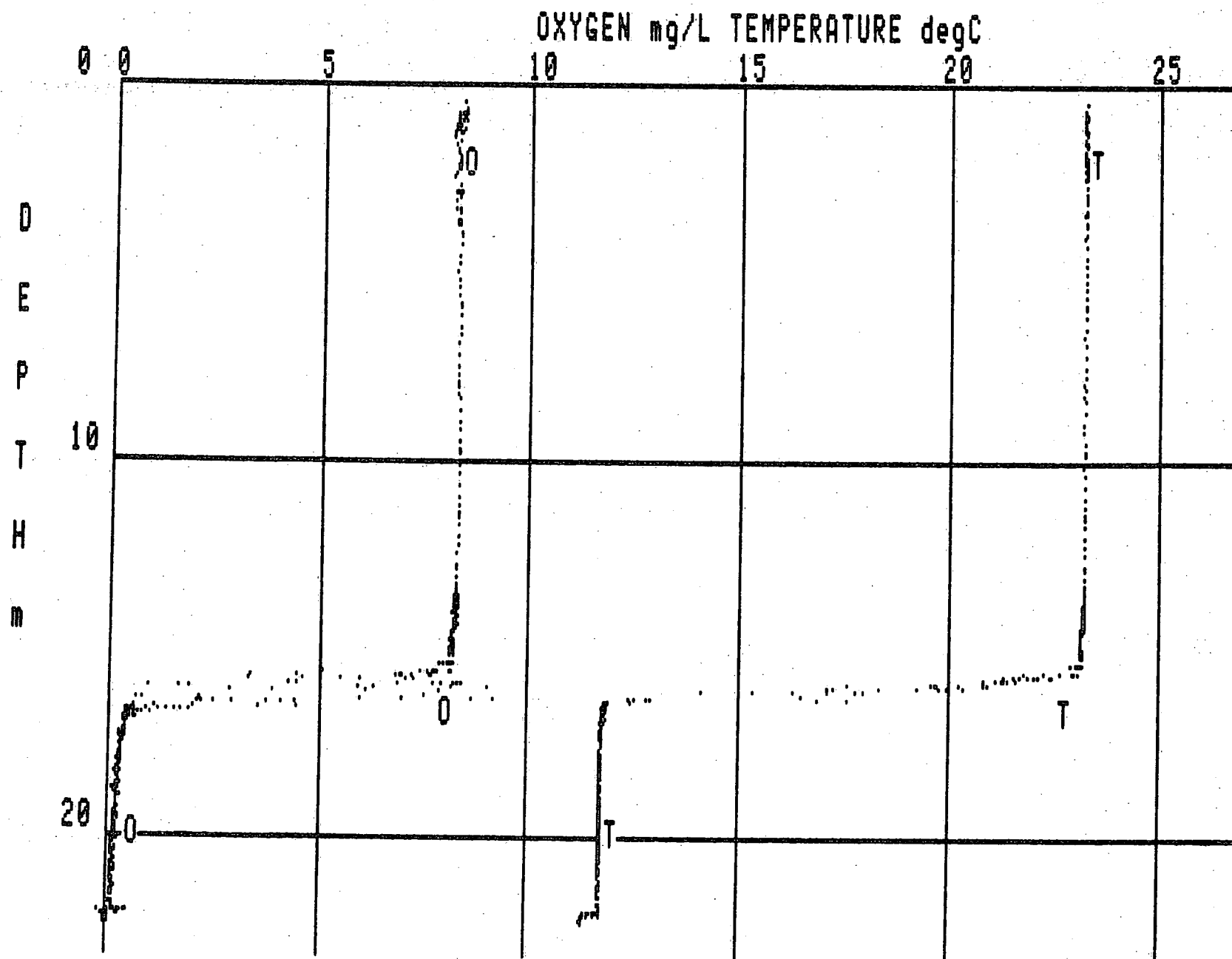


FIGURE 13. POOR PROFILE-CORRECTED WITH FOUR-PAIR FILTER

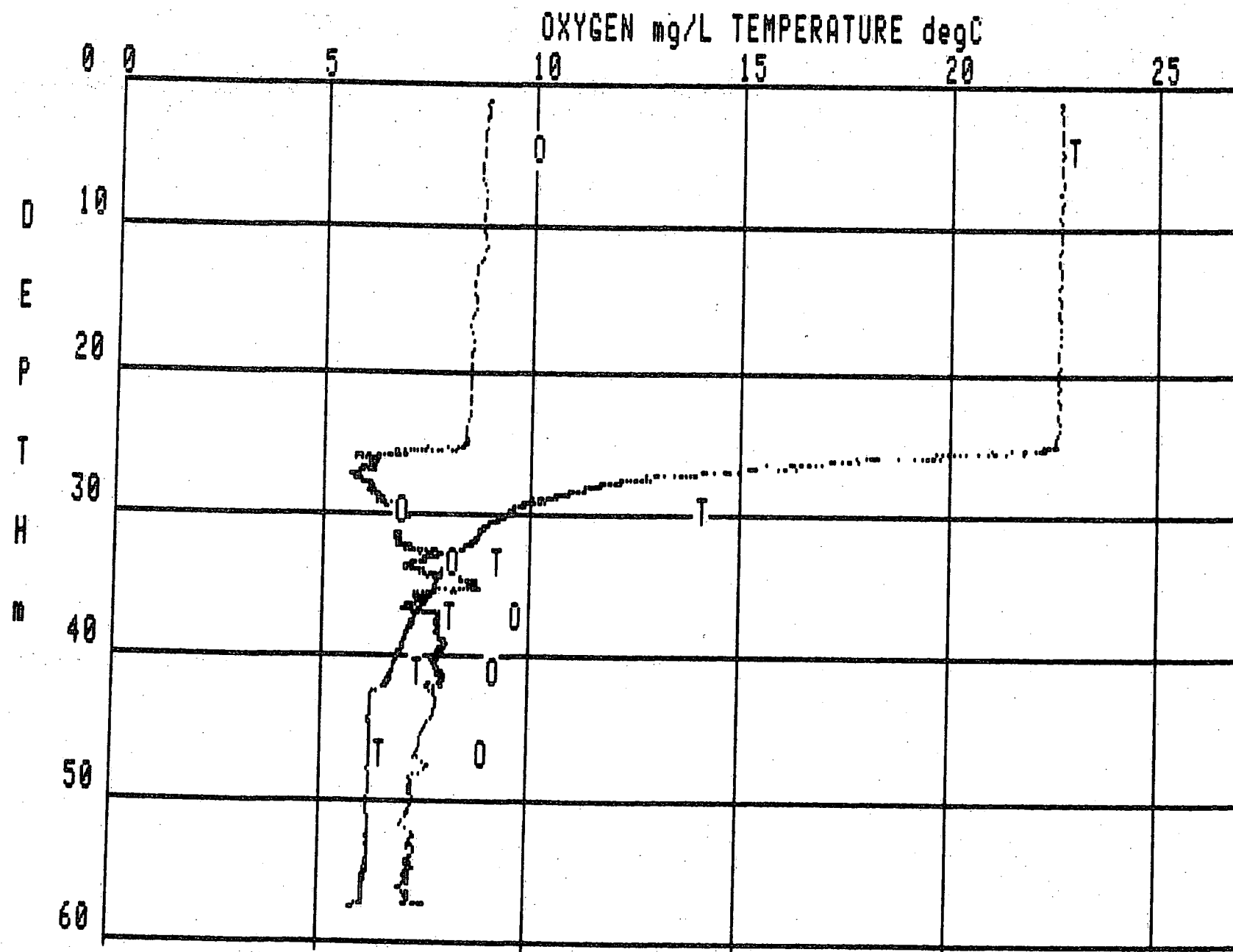


FIGURE 14. COMPLEX PROFILE - CORRECTED WITH FOUR-PAIR FILTER

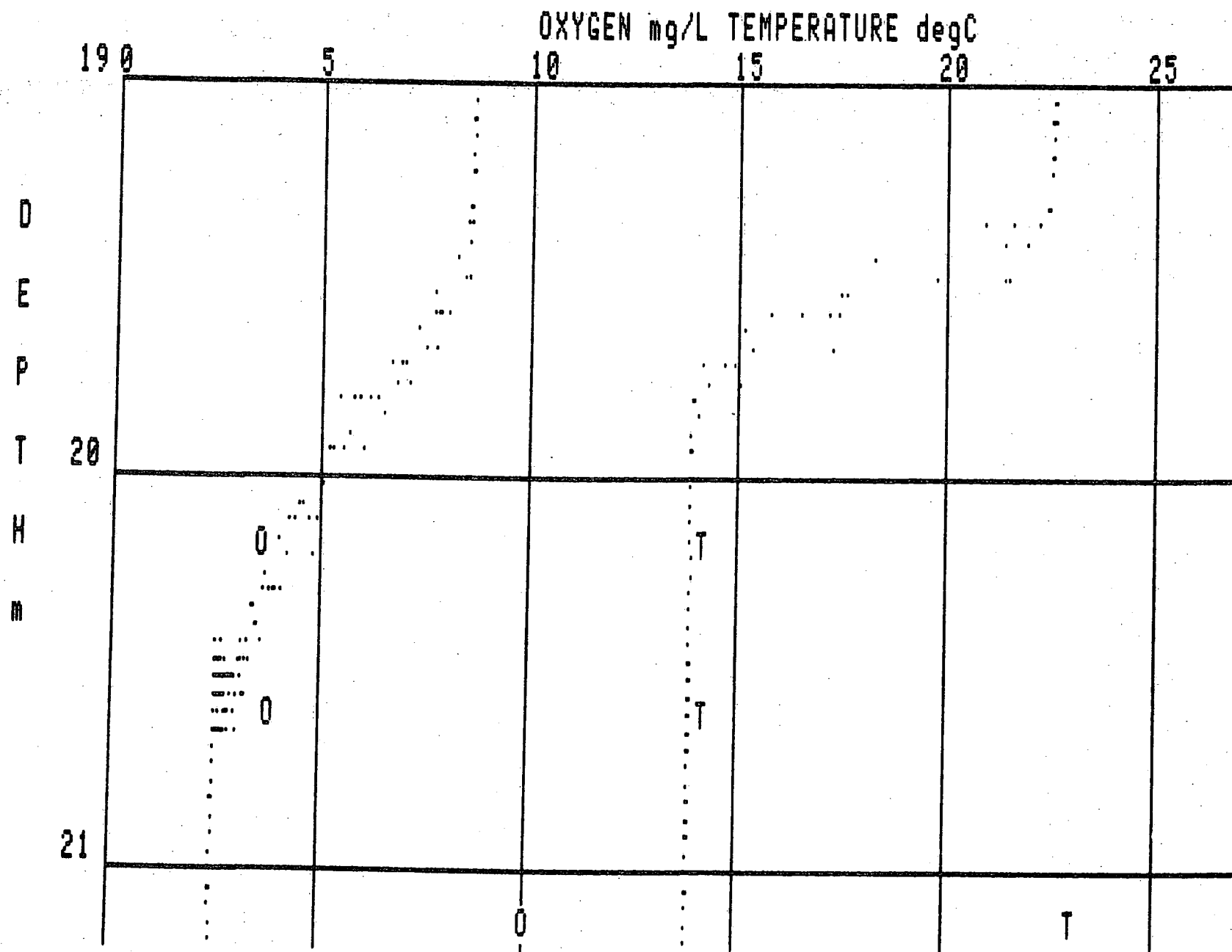


FIGURE 15. SHARP TRANSITION PROFILE - UNCORRECTED

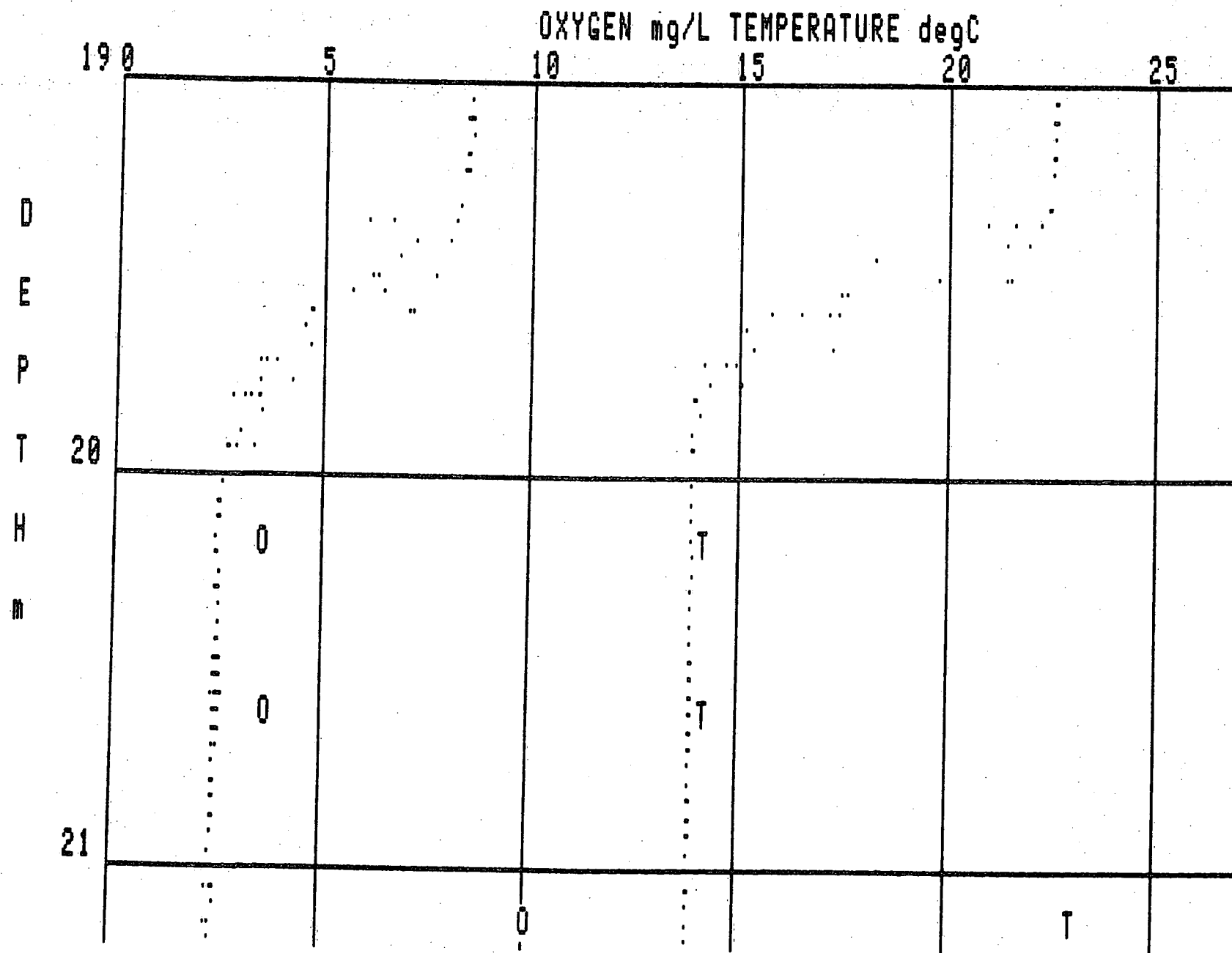


FIGURE 16. SHARP TRANSITION PROFILE - CORRECTED WITH FOUR-PAIR FILTER

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