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Hamon Portable Salinometers N.I.O. Version

CALIBRATION AND CHOICE OF COMPONENTS

by

M. J. TUCKER, J. MOOREY and R. A. COX

PLEASE TREAT THIS REPORT IN CONFIDENCE

It has been prepared to facilitate the commercial manufacture of these instruments, and the information it contains must not be passed on without the written consent of the Director of the N. I. O., nor must it be quoted in a bibliography.

N. I. O. Internal Report No. C3

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Note. values in this rept are for normal unit with cell constant of 5.5 & cable resitance of 2.6Ω for 100m.

Special deep unit 4865/11. has cell constant of about 8 & cable resitance 13Ω

HAMON PORTABLE SALINOMETERS: N.I.O. VERSION

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this will particularly effect R21 make it bigger

& also slightly effect R23 R28 R29

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C O N T E N T S

FIGURES

Circuit Compmnents

SECTION 1 : PRINCIPLES

1.0 General

It will be assumed that the reader is familiar with the general principles of the instrument as described by Hamon (Hamon, B.V. "A portable temperature-chlorinity bridge for estuarine investigations and sea water analysis", *J. Sci. Instrumen.*, Vol. 33, pp. 329-333, Sept. 1956). The N.I.O. version of this instrument differs from that described by Hamon in being transistorised, and in some minor details of the bridge circuit. A considerable number of these instruments is likely to be made, so it was thought advisable to describe the principles and practice for the engraving of scales, the calibration of cells and thermistors, the choice of bridge components and the testing of the completed instrument.

It is perhaps worth pointing out here that the scale engraving must not depend on the characteristics of individual cells or thermistors, since these are fragile and may have to be replaced. Also, of course, individually-engraved scales would considerably increase production costs.

On the question of accuracy, there are numerous factors which can introduce errors into the measurements made by the bridge, and it is therefore necessary to keep any individual controllable error to considerably less than the maximum permissible overall error: a factor of 5 is commonly accepted in these circumstances.

We have also assumed that the cells will be used either with 10 yards of cable, in which case the cable impedances may be neglected, or with 100 yards of a specific type of cable (which is the maximum length permissible).

1.1 The bridge with negligible cable impedances

This is the case when the measuring-head cable is 10 m. or less in length.

1.1(a) The salinity bridge (Figure 1).

This is discussed first here because it governs the choice of R_{23} which in turn governs the arrangement of the temperature bridge.

The thermistor compensates the variation of the resistance of the salinity cell with temperature, but by itself it would overcompensate. A fixed resistance R_{23} is therefore connected in series with it and is chosen to give the best possible compensation over the temperature range 0 to 20°C, using the criterion

$$\frac{(R_{23} + R_T) \text{ at } 5^\circ C}{(R_{23} + R_T) \text{ at } 15^\circ C} = \frac{R_c \text{ at } 5^\circ C}{R_c \text{ at } 15^\circ C} = \frac{L_{15}}{L_5}$$

where L_{15} and L_5 are the conductivities of sea water of S = 35‰ at 15°C and 5°C respectively.

P_2 is the measuring potentiometer.

In the "fixed arm", R_{21} is shunted by a trimming network (R_{27} and P_4) which allows small drifts in the cell constant or thermistor calibrations to be compensated.

R_4 and R_5 may be switched into circuit to provide an expanded scale on the 32‰ to 38‰ range of the instrument.

Considering first the 0 to 32‰ scale, if P_2 is assumed to be linear, with a resistance of R_{p2} per degree of shaft rotation, and θ is the angle of rotation of the shaft from the position of zero resistance, then Z, the resistance of the bridge arm containing P_2, is given by

$$Z = \theta R_{p2}$$

If R'_{21} is the resistance of the bridge arm containing R_{21}, then when the bridge is balanced

$$Z = R'_{21}\,(R_{23} + R_T)/R_C$$

$$= R'_{21}\,(R_{23} + R_T).KL$$

where K is a constant depending on the dimensions of the salinity cell, and L is the conductivity of the water

$$\text{or} \qquad \theta = R'_{21}\,(R_{23} + R_T)\,KL/R_{p2}$$

The scale is calibrated so that it is correct at a temperature of 15°C, giving

$$\theta = A \,.\, L_{15^\circ C}$$

$$\text{where} \quad A = R'_{21}\,(R_{23} + R_{T15^\circ C})\,K/R_{p2}$$

Now this is the only equation governing the choice of R'_{21}, so that A may be made a constant for all instruments by adjusting R_{21} to suit the values of R_{23}, $R_{T15^\circ C}$, K and R_{p2} in each individual instrument. Thus, a universal scale is possible, and for historic reasons. A has been chosen so that

$$\theta = 7{\cdot}3044 \times 10^3\, L_{15^\circ C}$$

For the calculation of this scale, the values of $L_{15^\circ C}$ at various salinities have been taken from the values given by Thomas, Thompson and Utterback (1934).

R_4 and R_5 are chosen to give a suitable expanded scale on the 32‰ to 38‰ range. On this range

$$\frac{1}{Z} = \frac{1}{R_5} + \frac{1}{R_4 + \theta\, R_{p2}}$$

If the same value of R_{21} is to be used, then at balance

$$Z = R'_{21}\,(R_{23} + R_{T15})\,K\,L_{15^\circ C}$$

or, inserting the equation for A given above,

$$Z = A\,R_{p2}\,L_{15^\circ C}$$

Thus,

$$\frac{1}{A\,L_{15^\circ C}\,R_{p2}} = \frac{1}{R_5} + \frac{1}{R_4 + \theta\,R_{p2}}$$

The values of R_4 and R_5 are chosen by putting in convenient values of θ for $L_{15^\circ C}$ at S = 32‰, and at S = 38‰. This gives two simultaneous equations from which R_4 and R_5 may be determined. The values obtained are not critical and could be "rounded off", but for historic reasons the following values are used

$$R_4 = 627{\cdot}3\,R_{p2}$$

$$R_5 = 532{\cdot}5\,R_{p2}$$

Having fixed these values, the scale must, of course, be engraved in precisely the correct relationship to the 0 to 32‰ scale.

The above equation now becomes

$$\frac{1}{7{\cdot}3044 \times 10^3 \; L_{15^\circ C}} = \frac{1}{532{\cdot}5} + \frac{1}{627{\cdot}3 + \theta}$$

from which the values of θ may be calculated for the various values of $L_{15^\circ C}$.

For this range, the value of $L_{15^\circ C}$ at 32‰ used is that given by Thomas, Thompson and Utterback, but for the rest of the scale the more accurate relative values given in the Handbook for the Thermostat Salinity Meter (N.I.O. Handbook No. H12) have been used. These values were measured on the thermostat salinity meter, which is in effect a precise conductivity comparator.

R_{21} is found by setting up the instrument with the cell in water of known salinity, connecting a resistance box in place of R_{21}, and adjusting it till the correct dial reading is obtained.

1.1(b) Effect of cell polarisation

Cell polarisation has approximately the same effect as connecting a large capacitor in series with the cell resistance. In the present cell it produces a phase-shift of about 2°. Since this phase-shift is small it does not appreciably affect the accuracy of the resistance balance (assuming that the resistance trimmer is set to give the correct reading in the centre of the 32 to 38‰ range), but the out-of-phase signal is sufficient to cause trouble in the amplifier and detector circuits and therefore has to be balanced out. Once again, because the phase-shift is small, this may be done without appreciable loss in accuracy by connecting a small capacitor C_1 in parallel with R_{21}, instead of a large capacitor in series with this resistance.

1.1(c) Temperature bridge (Figure 2)

R_{23} has already been fixed to make

$$\frac{(R_T + R_{23}) \text{ at } 5^\circ C}{R_T + R_{23} \text{ at } 15^\circ C}$$

a value which is the same for all instruments. In practice, this makes the proportional variation of the resistance of this arm with temperature follow the same law for all thermistors within the accuracy required, and so once again a similar dial may be used for all instruments.

R_1 is chosen to give a suitable scale on P_1, but once the dial has been engraved, the ratio of R_1 to P_1 must be kept constant. The scale is calculated from the measured characteristics of the thermistors. In practice, to facilitate setting-up the bridge, P_1 is set so that it reads $10\,\Omega$ with the dial set at $0^\circ C$, and R_1 is chosen so that

$$R_1 = 273{\cdot}8 \; R_{p1} - 10\,\Omega$$

$$= 1{\cdot}521 \; P_1 \; (180) - 10\,\Omega$$

Where P1(180) is the resistance change in P1 for 180° rotation

R_2 is chosen arbitrarily at some convenient value.

R_{22} then depends on the value of the thermistor resistance at some standard temperature, and is determined by placing the cell in water of known temperature, connecting a resistance box in place of R_{22}, and adjusting it until the correct dial reading is obtained.

1.2 The bridge with a long cable in series with the measuring head

1.2(a) The salinity bridge

Figure 3 shows the salinity bridge as it appears with 100 yards (92 m.) of cable type Telcon K 23 M connected in series with the measuring head.

(i) The effect of cable capacitances

The capacitances across the cell and thermistor arms partially compensate, but since the thermistor has nearly twice the resistance of the cell arm, it would be expected that an extra capacitor would have to be connected across the cell to produce balance. However, it so happens that the polarisation effect in the cell works in this sense and is slightly too large, so that in practice a small shunt capacitor C_1 has to be connected across R_{21}.

If capacitance balance is achieved at S = 35‰ and 15°C, it will not be correct at other temperatures and salinities. The effects of this are discussed in detail in Section 1.2(c).

(ii) Effect of cable resistances

To obtain the best temperature compensation with negligible cable resistance, R_{23} was chosen so that

$$\frac{(R_{23} + R_T) \text{ at } 5^\circ C}{(R_{23} + R_T) \text{ at } 15^\circ C} = \frac{R_C \text{ at } 5^\circ C}{R_C \text{ at } 15^\circ C} = \frac{L_{15}}{L_5}$$

where L is the conductivity of sea water.

The equivalent criterion with 2·4 Ω cable resistance is

$$\frac{(R'_{23} + 2{\cdot}4 + R_T) \text{ at } 5^\circ C}{(R'_{23} + 2{\cdot}4 + R_T) \text{ at } 15^\circ C} = \frac{(R_C + 2{\cdot}4) \text{ at } 5^\circ C}{(R_C + 2{\cdot}4) \text{ at } 15^\circ C}$$

From this it can be shown that

$$R'_{23} - R_{23} = 2{\cdot}4 \left(\frac{R_{23} + R_T \text{ at } 15^\circ C}{R_C \text{ at } 15^\circ C} - 1 \right)$$

Or, since the resistance of the P_2 arm at a setting of 35‰ is 1·74 x resistance of P_2 for 180° rotation,

$$R'_{23} - R_{23} = 2{\cdot}4 \left(\frac{1{\cdot}74 \, P_2 \, (180)}{R_{21}} - 1 \right)$$

For this purpose $P_2(180)$ and R_{21} need to be known to only about ±4%, so that this expression may be found to be effectively constant in practice for cells coming from the same mould, and thermistors from the same batch.

An additional effect of the cable resistance is that the proportional variation in the resistance of the whole cell arm with changes in salinity will be reduced and the scale will be significantly contracted. It can be shown that this effect can be precisely compensated (at a given temperature) by shunting the variable arm P_2 by a resistance R_{28} given by

$$2{\cdot}4 \, R_{28} = R_{21} \, (R'_{23} + 2{\cdot}5 + R_T)$$

In practice R_{28} is calculated for R_T at 15°C, and the errors at other temperatures will be small.

1.2(b) The temperature bridge

The temperature bridge with a long cable is shown in Figure 4.

The effect of cable capacitance can be balanced by C_{11}, and if this is done at the centre of the temperature range, variations in the capacitative balance at other temperatures will not affect the resistive balance as long as the phase-shift in the detector amplifier is within the prescribed limits of ±2°.

If the bridge is set to give the correct reading at the centre of the scale (15°C), the extra resistance in the thermistor arm (i.e., $R'_{23} - R_{23} + 2{\cdot}4\ \Omega + 0{\cdot}6\ \Omega \simeq 5\ \Omega$) will give an appreciable contraction of the scale. The obvious solution of switching in a lower value resistance for R'_{23} is inconvenient, and the same effect can be obtained precisely by shunting the $P_1 + R_1$ arm by a resistor R_{29} given by

$$(R'_{23} - R_{23} + 2{\cdot}4 + 0{\cdot}6)\, R_{29} = R_2\, R'_{22}$$

where R'_{22} is the resistance of the arm containing R_{22}.

Since the $P_1 + R_1$ arm is switched in any case, R_{29} can be left in circuit and requires no extra switch contacts.

1.2(c) The phase-shift of the amplifier

It has been pointed out briefly in Section 1.2(a)(i) that large out-of-phase signals are produced by the bridge under some circumstances, and these have to be rejected by the phase-sensitive rectifier. If the phase relationships in the system are incorrect, the out-of-phase components will produce a D.C. output on the meter which is compensated by a departure from the correct resistive balance, thus introducing an error. This effect turns out to be surprisingly critical.

It is easiest to see the cause of the effect by considering the temperature bridge (Figure 4). Assuming for the moment that R'_{23} is negligibly small, the condition for capacitance balance is

$$0{\cdot}016\, R_T = C_{11}\, R_{22}$$

C_{11} is chosen to give the correct value at 15°C, and is typically 0·01 μ F.

At 0°C, R_T has increased by approximately 70%, and to achieve balance, C_{11} would have to be increased in the same proportion. Since it is, in fact, fixed, an output is obtained approximately equivalent to removing an 0·007 μ F capacitor across C_{11}, which in turn is approximately equal in effect but opposite in sign to adding an 0·007 μ F capacitor across C_{11}. The voltage produced is equal to that given by a temperature change of rather more than 0·5°C. Thus, if the output produced is to be equivalent. to less than 0·02°C, the phase relationships must be correct to about 2·5° in angle.

The correct amplifier phase-shift is not zero, which might be expected at first sight, because the capacitance is not connected across a pure resistance. Assuming for the moment that the bridge supply is low impedance, the capacitance is connected effectively across the thermistor arm and the R_{22} arm in parallel, and these have shunt capacitances giving a phase-lag of between 3° and 4°. The correct amplifier phase-shift is therefore a phase advance of about 3°.

The approximations in the above argument do not matter, because in practice the phase-shift is set empirically.

Considering the salinity bridge, this is difficult to treat theoretically because we do not know the way the polarisation phase-shift in the cell varies with salinity and temperature. However, tests indicate that the 32‰ to 38‰ range is the most critical, and that at 35‰, a change from 15°C to 0°C requires an increased capacitance across the cell of about 0·005 μF. For this to have a negligible effect, the amplifier phase-shift must be correct to within about ±1° in angle.

A further complication is that the amplifier phase-shift required is not quite the same for the two bridges, because the phase-angle of the impedance of the bridge arms is slightly different. However, in practice, if the phase is adjusted to be correct for the salinity bridge, it is not significantly wrong for the temperature bridge. The reverse is not true.

1.3 The accuracy required in calibration and the tolerance on components

1.3(a) General

When a calibration involves several sources of error, a commonly-used criterion is that each individual error should be kept to 1/5th of the overall accuracy required. In the present case the specified overall accuracy is ±0·03‰ (on the S = 32‰ to 38‰ scale) in salinity and ±0·1°C. To follow the above rule would involve calibration of the cell with water samples whose salinity is known to ±0·007‰ and to calibrate the thermistors at temperatures known to ±0·007°C (see below). Most oceanographic laboratories have access to a thermostat conductivity salinity meter which will give the accuracy in salinity, but it is more difficult to get the temperature accuracy. However, an accuracy of 0·01°C should be possible and is probably adequate. In any case, the final check on the instrument will show if the errors have accumulated to an unacceptable extent.

In the case of the temperature scale and the S = 32‰ to 38‰ scale, the trimmers P_3 and P_4 respectively are set so that the scales read correctly at their mid-points. Thus, errors in the choice of the bridge components expand or contract the scales about these points, or spoil the temperature compensation.

1.3(b) The thermistors

The resistance of the thermistors is measured at 5°C and 15°C. If the error in temperature measurement is E(T), this can give an error of 2E(T) over a temperature difference of 10°C. Assuming the instrument is set before use to give the correct reading at 15°C, this would allow an error of approximately 3E(T) at 0°C and 30°C. Thus, using the criterion mentioned in Section 1.3(a), E(T) should be ±0·007°C. In practice, as already mentioned, it is probably not practicable to achieve better than ±0·01°C (using a multiple thermocouple, for example).

The resistance of the thermistors changes approximately 3·4% per °C, so that the accuracy of measurement required, corresponding to ±0·007°C, is approximately 2 in 10^4, or 0·05 Ω in a 250 Ω thermistor. (Note that it is the ratio of resistances at 5°C and 15°C which is critical. An error in the absolute value is roughly three times less important.)

A further problem arises because the power dissipated in the thermistor by the bridge voltage can appreciably raise its temperature, and for this reason it should be measured with a bridge which causes 0·1 Vr.m.s. or less to appear across the thermistor.

Similar reasoning applied to the salinity bridge shows that the above accuracy is adequate for the temperature compensation.

1.3(c) The resistors and potentiometers

(i) R_{23}

When dealing with the accuracy required in the main bridge resistors, we may neglect the cable impedances.

Considering the salinity bridge (Figure 1), R_{23} is chosen (see Section 1.1(a)) to give optimum temperature compensation, that is, so that

$$\frac{(R_{23} + R_T) \text{ at } 5^\circ C}{(R_{23} + R_T) \text{ at } 15^\circ C} = \frac{L_{15}}{L_5}$$

If a small error ΔR_{23} is made in R_{23} and the bridge is balanced at $15^\circ C$ and $S = 35‰$, then if the bridge is to remain balanced at $5^\circ C$, a small change in conductivity to L'_5 is required where

$$\frac{(R_{23} + \Delta R_{23} + R_T) \text{ at } 5^\circ C}{(R_{23} + \Delta R_{23} + R_T) \text{ at } 15^\circ C} = \frac{L_{15}}{L'_5}$$

Neglecting second order terms this gives

$$L'_5 = L_5 \left(1 + \frac{\Delta R_{23}}{R_{23} + R_T \text{ at } 15^\circ C} \cdot \frac{L_{15} - L_5}{L_5}\right)$$

$$= L_5 \left(1 + 0{\cdot}28 \frac{\Delta R_{23}}{R_{23} + R_T \text{ at } 15^\circ C}\right)$$

Since L is approximately proportional to $(\text{salinity})^{-1}$, the proportional error in salinity is approximately $0{\cdot}28\ \Delta R_{23}/(R_{23} + R_T$ at $15^\circ C)$. Thus, the maximum allowable ΔR_{23} is given by

$$\Delta R_{23} \max = \pm\frac{0{\cdot}007}{35} \cdot \frac{1}{0{\cdot}28}\left(R_{23} + R_T \text{ at } 15^\circ C\right)$$

$$\simeq \pm 0{\cdot}25\ \Omega$$

A similar calculation for the temperature bridge shows that an error of $\pm 0{\cdot}65\ \Omega$ in R_{23} can be tolerated, so that the accuracy required for the salinity bridge is the controlling factor.

At first sight this may appear inconsistent with the accuracy of $0{\cdot}05\ \Omega$ demanded in the calibration of the thermistors (Section 1.3(b)). However, the <u>difference</u> in the calibration errors at $5^\circ C$ and $15^\circ C$ has an exaggerated effect in expanding or contracting the temperature scale, whereas the main effect of an error in R_{23} is to alter the scale zero, which can be corrected by the trimmer and is therefore unimportant, and its effect in expanding or contracting the scale is comparatively small.

(ii) <u>R_1 and P_1</u>

It is the ratio of R_1 to P_1 which is critical. Changes in the absolute value can be compensated by adjusting R_{22}.

In practice, to avoid using the non-linear end portion of the potentiometer, P_1 is set so that when the dial reads $0^\circ C$, it has a resistance of $10\ \Omega$.

If the potentiometer resistance at $15^\circ C$ on the dial is $P_{15} + 10\Omega$, then the design value of R_1 is given by

$$\frac{P_{15} + R_1 + 10}{R_1 + 10} = \frac{(R_{23} + R_T) \text{ at } 0^\circ C}{(R_{23} + R_T) \text{ at } 15^\circ C} = Y, \text{ say}$$

From which $P_{15} = (Y - 1)(R_1 + 10) \simeq 0{\cdot}45\ (R_1 + 10)$

Now if R_1 is in error by ΔR_1, and the trimmer P_3 has been adjusted so that the dial reads correctly at 15°C, then with the cell precisely at 0°C, the bridge will balance with P_1 having a resistance of $10\ \Omega + \Delta P_1$ such that

$$\frac{P_{15} + R_1 + \Delta R_1 + 10}{R_1 + \Delta R_1 + \Delta P_1 + 10} = Y = \frac{P_{15} + R_1 + 10}{R_1 + 10}$$

Giving

$$\Delta R_1 = \frac{Y}{1 - Y}\ \Delta P_1$$

$$\simeq -3{\cdot}22\ \Delta P_1$$

Near 0°C, an 0·02°C change in dial setting is given by a shaft rotation of 0·16°, so that

$$\Delta R_1 \max = \pm\ 3{\cdot}22 \times 0{\cdot}16\ R_{p1}$$

$$= \pm\ 0{\cdot}52\ R_{p1}$$

$$\simeq \pm\ 0{\cdot}43\ \Omega$$

$$\text{or} \quad \frac{\Delta R_1 \max}{R_1} \simeq \pm\ 0{\cdot}002$$

Since it is the ratio of R_1 to P_1 which is important, the resistance of P_1 must be measured to the same proportional accuracy.

(iii) <u>R_4, R_5 and P_2</u>

Errors in these resistors have two effects:

(a) Assuming that the trimmer is set so that the bridge reads correctly at 35‰ on the 32‰ to 38‰ scale, then an error will be introduced when the bridge is switched to the 0 to 32‰ scale.

(b) They will expand or contract the scale width on the 32‰ to 38‰ scale.

Treating effect (a) first, on the 32‰ to 38‰ scale

$$\frac{1}{Z} = \frac{1}{R_5} + \frac{1}{R_4 + P_2}$$

The bridge is trimmed with P_2 set at 35‰, where $P_2 = 133{\cdot}1\ R_{p2}$ (R_{p2} = resistance per unit angle of P_2).

With the correct values of R_4 and R_5, this gives $Z = 312{\cdot}9\ R_{p2}$.

However, if R_4 is increased by a small amount ΔR_4, and R_5 by a small amount ΔR_5, the value becomes

$$Z + \Delta Z = 312{\cdot}9\ R_{p2} + 0{\cdot}17\ \Delta R_4 + 0{\cdot}35\ \Delta R_5$$

(This is derived by differentiation of the expression for Z and putting in the nominal values of R_4 and R_5.)

Thus the trimmer arm has been changed by a proportion $\Delta Z/Z$, and will give this proportional error when the bridge is switched to the 0‰ to 32‰ scale. On this scale, the accuracy specified is 0·1‰, or 1 part in 320, and the maximum allowable ΔZ is therefore given by

$$\frac{\Delta Z_{max}}{Z} = \frac{1}{5 \times 320}$$

$$\text{or } \Delta Z_{max} = \pm 0{\cdot}20 \ R_{p2}$$

$$\text{or } \Delta R_4 \text{ max} \approx \pm \frac{0{\cdot}20}{0{\cdot}17} R_{p2} \approx \pm 1\,\Omega$$

$$\text{and } \Delta R_5 \text{ max} \approx \pm \frac{0{\cdot}20}{0{\cdot}35} R_{p2} \approx \pm 0{\cdot}5\,\Omega$$

If the value of R_{p2}, the resistance per unit angle of P_2, has been incorrectly measured, the calculated values of R_4 and R_5 will be in error in the same proportion, and Z at 35‰ will be in error by very nearly this proportion. Thus, R_{p2} must be measured to an accuracy of 1 in 5 x 320 = 0·07%.

With regard to effect (b), suppose that for a salinity S the bridge balances with P_2 at an angular position Θ. Then a measure of the scale width is $X = ds/d\Theta$ (this is more convenient than $d\Theta/ds$).

This expression can be changed into more convenient terms as follows -

$$X = \frac{dS}{d\Theta} = \frac{dS}{dP_2} \cdot \frac{dP_2}{d\Theta}$$

Now for the present calculations it is sufficiently accurate to assume that the cell resistance is proportional to 1/S or at balance, $Z \propto S$.

Thus $$\frac{dS}{S} = \frac{dZ}{Z}$$

Also $$\frac{dP_2}{d\Theta} = R_{p2}$$

Thus $$X = \frac{dZ}{dP_2} \cdot \frac{S}{Z} \cdot R_{p2}$$

Writing down the expression for Z in terms of R_4, R_5 and P_2 and differentiating gives

$$\frac{dZ}{dP_2} = \frac{R_5^{\,2}}{(R_4 + R_5 + P_2)^2} = \frac{Z\,R_5}{(R_4 + P_2)(R_4 + R_5 + P_2)}$$

From which $$X = S\,R_{p2}\,\frac{R_5}{(R_4 + P_2)(R_4 + R_5 + P_2)}$$

Consider the situation when S = 35‰. A small error ΔR_5 introduced into R_5 is first compensated by trimming P_4 to give the same reading on P_2. Thus, the effect on scale width is

$$\Delta X = \Delta R_5 \left(\frac{\partial x}{\partial R_5}\right)_{R_4 P_2 \text{const.}} = \frac{S\,R_{p2}}{(R_4 + R_5 + P_2)^2}\,\Delta R_5$$

$$\text{or} \quad \frac{\Delta X}{X} = \frac{R_4 + P_2}{(R_4 + R_5 + P_2)}\,\frac{\Delta R_5}{R_5}$$

$$= 0{\cdot}63\,\frac{\Delta R_5}{R_5}$$

The specified accuracy of $\frac{\Delta X}{X}$ is 1 in 100, so that using the 1/5 criterion

$$\Delta R_5 \text{ max } \simeq \pm 3{\cdot}0 \times 10^{-3} R_5$$

The similar equation for ΔR_4 is

$$\frac{\Delta X}{X} = -1{\cdot}34 \frac{\Delta R_4}{R_4}$$

$$\text{or} \qquad \Delta R_4 \text{ max } = \pm 1{\cdot}5 \times 10^{-3} R_4$$

so that the previous criteria are the controlling ones.

Suppose we now change R_{p2} from its correct value by an amount ΔR_{p2}. This will make a change in zero which will be compensated by the trimmer, and it will cause a scale change ΔX given by

$$\Delta X = \Delta R_{p2} \left(\frac{\partial X}{\partial R_{p2}}\right)_{R_4,\ R_5 \text{ const.}}$$

Putting in that $P_2 = 133\ R_{p2}$ at 35‰,

$$\frac{\Delta X}{X} = \frac{\Delta R_{p2}}{R_{p2}} \cdot \frac{R_4^2 + R_4R_5 - P_2^2}{(R_4 + P_2)(R_4 + R_5 + P_2)}$$

$$= 0{\cdot}775 \frac{\Delta R_{p2}}{R_{p2}}$$

Thus,

$$\Delta R_{p2} \text{ max } = \pm 2{\cdot}6 \times 10^{-3} R_{p2}$$

so that the effect (a) above produces the controlling accuracy here also.

Considering the accuracy necessary in the angular setting of the body of P_2 relative to the dial, the criterion is that the low salinity settings on the 0 to 32‰ range must be correct, since the zero of this range cannot be trimmed. The angular change is approximately 10° per ‰ at low salinities, so that the angle must be correct to 0·2°, equivalent to approximately 0·2 Ω.

(iv) <u>R_{21} and R_{22}</u>

These can be trimmed by approximately ±2%, so that it is quite sufficient to make them to ±0·5%.

(v) <u>R_{28} and R_{29}</u>

R_{28} and R_{29} are never less than about 40 times the resistance of the bridge arm which they are shunting, and an accuracy of ± 2% is therefore adequate.

1.4 Changing cells

R_{21} depends on the cell constant and on the thermistor resistance;

R_{22} depends on the thermistor resistance;

R_{23} depends on the thermistor characteristics.

These resistors therefore have to be changed when a cell is replaced.

$\left.\begin{array}{l} C_1 \\ C_{11} \\ R_{28} \\ R_{29} \end{array}\right\}$ These components depend on whether a long or short cable is used, and to some extent also on the thermistor and cell resistances. They must therefore also be readily changeable.

SECTION 2 : PRACTICAL ROUTINE FOR CALIBRATION OF THE CELLS AND THERMISTORS, CHOICE OF RESISTORS AND CAPACITORS, SETTING UP OF THE BRIDGE AND FINAL TESTING.

2.1 Table of accuracies required in measurements and of tolerances on bridge components

Component or process		Accuracy or tolerance	Proportional value
Calibration of thermistors:	temperature	0·01°C	-
	resistance	0·05 Ω	0·02%
Measurement of potentiometer resistance:			
Angular accuracy P_1	(temperature)	0·2°C	-
P_2	(salinity)	0·2°C	-
Resistance accuracy	P_1	0·3 Ω	0·2%
	P_2	0·1 Ω	0·07%
Setting the angular positions of the measuring potentiometers (by measuring resistance at a given dial setting)	P_1	0·4 Ω	-
	P_2	0·2 Ω	-
For selection of R_{21} and R_{22}:	temperature	0·1°C	-
	salinity	0·1‰	-
For final trimming and checking:	Temperature	0·02°C	-
	Salinity 32-38‰	0·007‰	-
	Salinity 0-32‰	0·02‰	-
Component tolerances:	R_1	0·4 Ω	0·2%
	R_2	-	1%
	R_4	0·25 Ω	0·05%
	R_5	0·5 Ω	0·1%
	R_{21}	0·5 Ω	0·5%
	R_{22}	1·5 Ω	0·5%
	R_{23} or R'_{23}	0·25 Ω	0·25%
	R_{26}	-	10%
	R_{27}	-	10%
	R_{28}	-	2%
	R_{29}	-	2%

(Cont.)

Component or process		Accuracy or tolerance	Proportional value
Component tolerances (cont.):	P_3	-	20%
	P_4	-	20%
	C_1	0·001μF	-
	C_{11}	0·001μF	-
Amplifier phase-shift		1°	-
Amplifier gain		-	30%

NOTE: All resistors and potentiometers in this list must be wound from low temperature-coefficient wire, except R_{26}, R_{27}, R_{28} and R_{29}, which may be grade 1 carbon, and P_3 and P_4, which are ordinary carbon-track potentiometers. Resistors to be wound non-inductively.

2.2 Practical routine

2.2(a) General

The measurements and calculations have to be performed in three stages:

Stage 1. As early as convenient the thermistors are calibrated, the potentiometers are checked for linearity and their resistances measured, and R_1, R_4, R_5 and R_{23} are calculated.

Stage 2. When the instruments have been completed except for the insertion of the components whose values are so far unknown, these values are determined by measurements and calculations. The electronics are also checked at this stage.

Stage 3. The final checks on accuracy are made, and a correction chart prepared if required by the customer.

N.B. Don't forget to note the serial numbers of the thermistors, potentiometers, salinity cells and completed bridges, and the date of the test on each sheet of paper used!

2.2(b) Stage 1. Calibration of the thermistors, checking the potentiometers and calculation of R_1, R_4, R_5 and R_{23}.

(i) The thermistors and R_{23}

The thermistors should be calibrated in a bridge such that the potential applied to them is not more than 0·1 V.

The values required are:- R_{T5} : the resistance at 5·00°C

R_{T15}: the resistance at 15·00°C

It is probably not practicable to hold the water bath precisely at the stated temperatures, and it is easier to allow the bath to drift slowly, to measure the resistances at two temperatures within 0·5° on either side, and to interpolate. The water bath must be well stirred, and silicone grease smeared over the top of the glass thermister tubes to prevent electrical leakage between the leads.

Calculate R_{23} from

$$R_{23} = 3{\cdot}557\, R_{T5} - 4{\cdot}557\, R_{T15}$$

The value usually comes out to between 75Ω and 105Ω.

If the instrument is to be used with a short cable on the measuring head, R_{23} can now be constructed using this value. If, however, the measuring head is to be used on a long cable, R'_{23} cannot be constructed until stage 2 (see section 2.2(c)(ii)).

(ii) P_1 (180) and P_2 (180), and R_1, R_4 and R_5.

Fix a protractor to the shaft of P_1 (used in the temperature bridge) and arrange it so that when the potentiometer is turned fully anticlockwise, the protractor reads approximately 0° (this is not critical).

Use a bridge to measure the resistance between the wiper and the left-hand terminal looking at the back with the terminals uppermost. Measure this resistance

P_{20} at 20° rotation
P_{50} at 50° rotation
P_{80} at 80° rotation
P_{140} at 140° rotation
P_{200} at 200° rotation
P_{230} at 230° rotation
P_{260} at 260° rotation

Calculate

$P_{200} - P_{20}$
$P_{230} - P_{50}$
$P_{260} - P_{80}$

Owing to the discrete turns, these values may differ by as much as $0{\cdot}7\Omega$. Take the average value and use this as $P_1(180)$. If they differ by more than $0{\cdot}7\Omega$ rotate the wiper several times to clean the wire and repeat the measurements.

Check that $P_{140} = \dfrac{P_{20} + P_{260}}{2} \pm 0{\cdot}6\,\Omega$

Note: Though these errors seem large compared with the accuracy of $\pm 0{\cdot}1\Omega$ demanded in the measurements, the maximum error in $P_2(180)$ should be approx. $0{\cdot}4\Omega$, and the likely error is considerably less than this. Also, controllable errors must be kept to a minimum so that they cannot contribute significantly to the overall error.

Measure the resistance $P_2(180)$ (the potentiometer used in the salinity bridge) in a similar manner.

From these values calculate

$$R_1 = [1{\cdot}521 \; P_1(180)] - 10\,\Omega$$
$$R_4 = 3{\cdot}487 \; P_2(180)$$
$$R_5 = 2{\cdot}960 \; P_2(180)$$

2.2(c) Stage 2. Determination of R_{21}, R_{22}, R'_{23}, R_{28}, R_{29}, C_1 and C_{11}, and checking the amplifier characteristics.

For this stage the instrument must be complete except for the above components.

If a short cable is used, R_{28} and R_{29} are omitted and R_{23} will already have been determined.

(i) Preliminary adjustments

First adjust the cursor of P_1 on its shaft so that when it reads $0^\circ C$, the resistance of P_1 is 10Ω (to the nearest step on the winding).

Similarly, adjust P_2 so that when the cursor reads 16‰ on the 0-32‰ scale, the resistance of P_2 is $0{\cdot}857\ P_2\ (180)$.

Adjust P_3 and P_4 to the middle of their working range (in terms of angle).

(ii) <u>R_{21}, R'_{23}, R_{28} and C_1</u>

Place the cell in a stirred bath of sea-water with a known salinity of between 34‰ and 36‰ and a temperature of between 13°C and 17°C.

If R_{23} is not already inserted, connect a resistance box in place of it and adjust it to approximately the correct value as follows:

$$R'_{23} \approx R_{23} + 4\Omega \text{ if a 100-yard cable is in use.}$$

Connect another resistance box in place of R_{21} and a capacitor box in place of C_1. Adjust R_{21} to 100Ω and C_1 to zero.

Turn the bridge switch to the 32‰ to 38‰ scale and switch on the instrument.

Use a C.R.O. to check that the bridge supply voltage is about 0•5 V pk. - pk. at 2•5 Kc/s.

Reconnect the C.R.O. to look at the voltage (A.C.) on the collector of the first amplifier transistor.

Set the dial of P_2 to the salinity of the bath and balance the bridge using the R_{21} and C_1 boxes. (The C.R.O. should have sufficient sensitivity to see a change of 0•1Ω in R_{21}, which should produce a voltage of approximately 5 mV pk. to pk. on the C.R.O.) If C_1 should apparently be negative, reconnect the capacitance box across the cell terminals.

Use this value of R_{21}, and the approximate value of R'_{23}, to calculate R_{28} as follows:

$$R_{28} = 0{\cdot}96\ R_{21}\ (R'_{23} + 2{\cdot}5 + R_T \text{ at } 15^\circ C)/2{\cdot}4\Omega$$

Insert this value of R_{28}. It should be possible to construct this by combining two Grade 1 ±10% carbon resistors.

Rebalance the bridge, and use the new value of R_{21} to calculate the exact value of R'_{23} as follows:

$$R'_{23} = R_{23} + [4{\cdot}2\ P_2\ (180)/R_{21}] - 2{\cdot}4\Omega$$

(R_{23} is the value determined in section 2.2(a)(i).)

Note this value of R'_{23}, set it up on the resistance box, and rebalance the bridge.

C_1 is now its final value, but the final value of R_{21} is 1% greater than the value now set up on the box (since P_3 in the middle of its angular range is not at the middle of its shunting effect).

Note these final values.

(iii) <u>Amplifier phase-shift</u>

The oscilloscope should be disconnected for this test.

Insert the correct capacitor in place of C_1, and reconnect the capacitance box across the salinity cell (the back of the cable socket on the panel is a suitable place). With the bridge connected as above and balanced, a change of 0•01μF in the capacitance across the cell should change the meter reading by the equivalent of less than 0•03‰.

If the change is greater than this value, C_{13} (across the amplifier output) must be adjusted until this condition is fulfilled.

N.B. It is essential that for this test the capacitance across the cell is changed, and not the capacitance of C_1.

(iv) R_{22}, R_{29} and C_{11}

Reconnect oscilloscope to look at voltage on the collector of first amplifier.

Leave the R'_{23} box set at its final value.

Reconnect the box from R_{21} to take the place of R_{22}.

Reconnect the capacitor box to take the place of C_{11}.

Switch to the temperature bridge and switch the instrument on.

Measure the temperature of the bath to ±0·1°C and adjust the temperature scale to read this value.

Balance the bridge using R_{22} and C_{11}.

Use this value of R_{22} to calculate R_{29} using the formula:

$$R_{29} = 390 \times 0{\cdot}96\, R_{22}/(R'_{23} - R_{23} + 2{\cdot}4 + 0{\cdot}6)\ \Omega$$

$$= 374\, R_{22}/[4{\cdot}2\, \frac{P_2\ (180)}{R_{21}} + 0{\cdot}6]\ \Omega$$

Insert this value of R_{29}. It should be possible to construct this by combining two Grade 1 ±10% carbon resistors.

Rebalance the bridge. (N.B. Make sure that the temperature of the bath has not drifted. If it has, re-adjust the dial.)

C_{11} is now its final value, but the final value of R_{22} is 1% greater than the value now set up on the box.

Note these final values.

(v) Amplifier gain

Remove the C.R.O.

Change the temperature dial by 0·5°C. The meter should deflect about 20μA.

2.2(d) Stage 3. Final checks and preparation of the correction chart.

For this stage the instrument should be complete in all details.

It consists of checking the instrument at a variety of precisely known temperatures and salinities.

(i) Trimming, using P_3 and P_4

Put the measuring head in a stirred bath whose salinity is precisely known and is as close as is practicable to 35‰, and whose temperature is precisely known and is as close as is practicable to 15°C. Set the dials to precisely the values of the bath, switch the bridge to the temperature range and bring the meter to zero using P_4, change to the 32‰ to 38‰ range, and again bring the meter to zero using P_3.

(ii) Final checks

The tests given here are suggested as the minimum check which should be given to each instrument. When the customer requires a more comprehensive test this should be undertaken by the N.I.O. who will issue a test certificate and charge a fee to cover the cost of the tests.

Prepare a series of stirred water-baths at roughly 5°C intervals from 0°C to 30°C (fresh water may be used for this test). Immerse the cell in each bath in turn, read the temperature to 0·1°C on a reliable thermometer, balance the bridge and note the dial reading. Prepare a table of corrections as follows:

True temperature	0·0°	5·2°	10·3°	....
Bridge reading	-0·1°	5·0°	10·4°	....
Correction to be applied to bridge reading	+0·1°	+0·2°	-0·1°	....

Prepare baths of sea water of salinities approximately 5‰, 15‰, 25‰ for the low range and 33‰, 35‰, 37‰ for the high range. These should be in thermally insulated containers (a large vacuum flask is suitable). Cool the water in advance to about 0°C, immerse the cells of the instruments and to prevent evaporation during the tests plug the neck of the flask with cotton wool. The bath must be equipped with a stirrer, a thermometer and an electric immersion heater. Stir until the water is uniform, balance the bridges and read the temperature. Switch on the heater until the temperature has reached about 10°C, again stir until uniform and read. Repeat at 20°C and 30°C.

Immediately after the series take a sample of the water and determine its salinity on a precision salinometer.

Repeat with the other salinities.

Prepare a table as follows:

True salinity	Reading of instrument under test			
	0°C	10°C	20°C	30°C
4·95‰	4·9	4·9	5·0	5·1
15·12‰	15·1	15·1	15·2	15·3
etc.				
37·04	37·10	37·06	37·05	37·02

CIRCUIT COMPONENTS

Circuit Diagram Symbol	Description		
P1		250Ω	25 W
P2		250Ω	25 W
P3		10KΩ	½ W
P4		10KΩ	½ W
R1		220Ω approx.	Wire wound
R2		390Ω "	" "
R4		530Ω "	" "
R5		450Ω "	" "
R6		470Ω	½ W
R7		22KΩ	½ W
R8		4·7KΩ	½ W
R9		1·5KΩ	½ W
R10		68KΩ	½ W
R11		10KΩ	½ W
R12		4·7KΩ	½ W
R13		1·5KΩ	½ W
R14		68KΩ	½ W
R15		10KΩ	½ W
R16		1·5KΩ	½ W
R17		470Ω	½ W
R18		2·2KΩ	½ W
R19		1KΩ	½ W
R20		1KΩ	½ W
R21		100Ω approx.	Wire wound
R22		300Ω "	" "
R23		80Ω "	" "
R24		150Ω	¼ W
R25		68Ω	¼ W
R26		4·7KΩ	½ W
R27		2·2KΩ	½ W
R28	depends on cable length		½ W
R29	" " " "		½ W
S1	Switch	8-pole 3-way wafer S/W	
S2	"		
C1	To be adjusted to cable length		
C2		0·01μF	
C3		0·5μF approx.	
C4		100μF	
C5		0·1μF	
C6		100μF	
C7		25μF	
C8		0·1μF	
C9		25μF	
C10		~~[illegible]~~ 5·0μF	
C11	To be adjusted to cable length		
C12		5μF	
C13		0·015μF approx.	
TR1	Transistor	OC 71	
TR2	"	OC 44	
TR3	"	OC 44	
MR1	Diode	CV 448 (OA 71) germanium	
MR2	"	" " "	
Th	Thermistor	(S.T.C. type F 22)	
T	Transformer	Ferroxcube LA.1	
M	Meter	50-0-50μA centre zero	
B	Battery	Batrymax 9V	

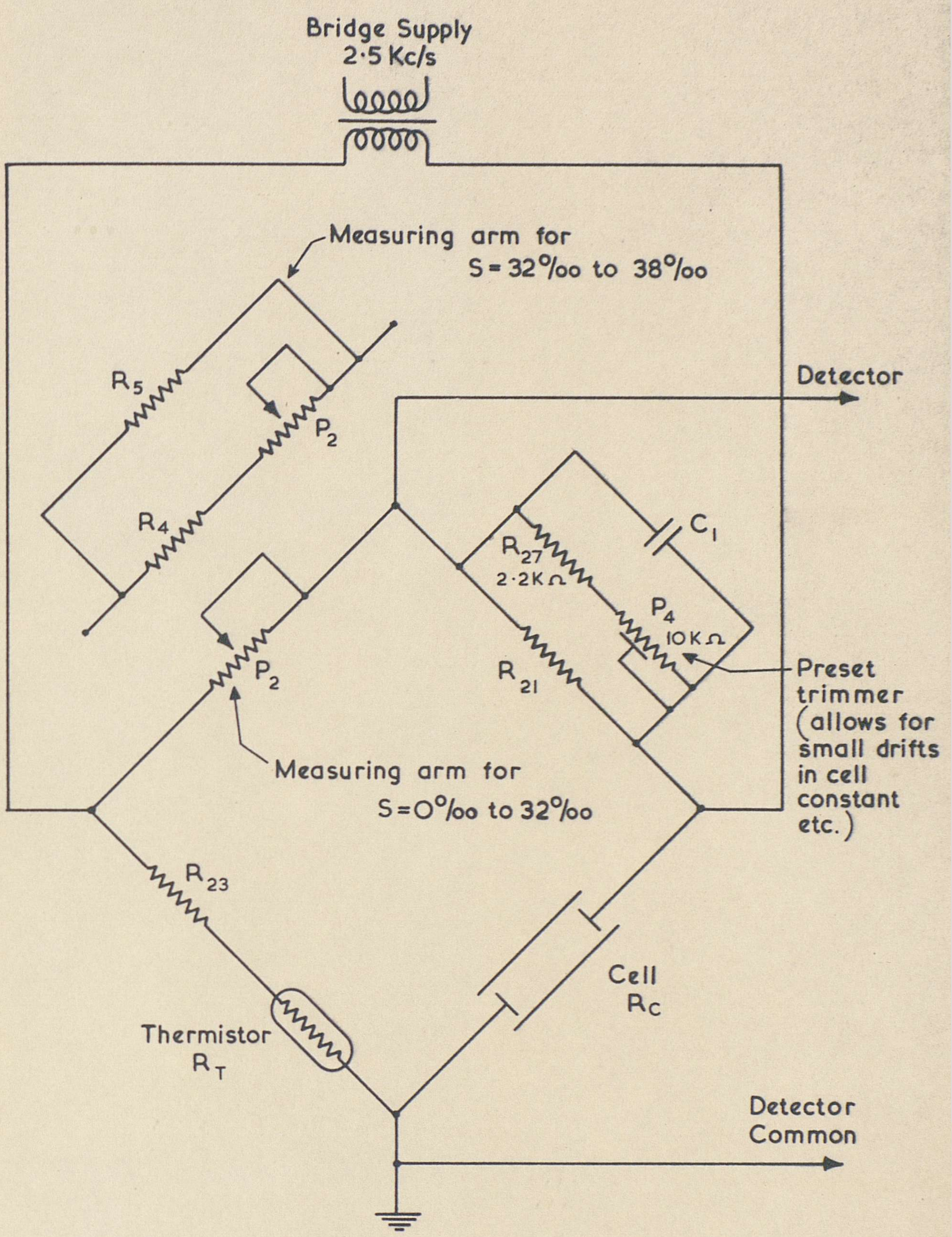


FIGURE 1

The salinity bridge with no appreciable cable impedances

Typical values are :—

$R_4 = 530\,\Omega$	$R_5 = 450\,\Omega$	$R_{21} = 100\,\Omega$	$R_{23} = 100\,\Omega$
$R_T = 250\,\Omega$	$R_C = 150\,\Omega$	$P_2 = 0$ to $250\,\Omega$	$C_1 = 0{\cdot}015\,\mu f$

($R21 \simeq 190\,\Omega$ on 4865/11 long lead unit)

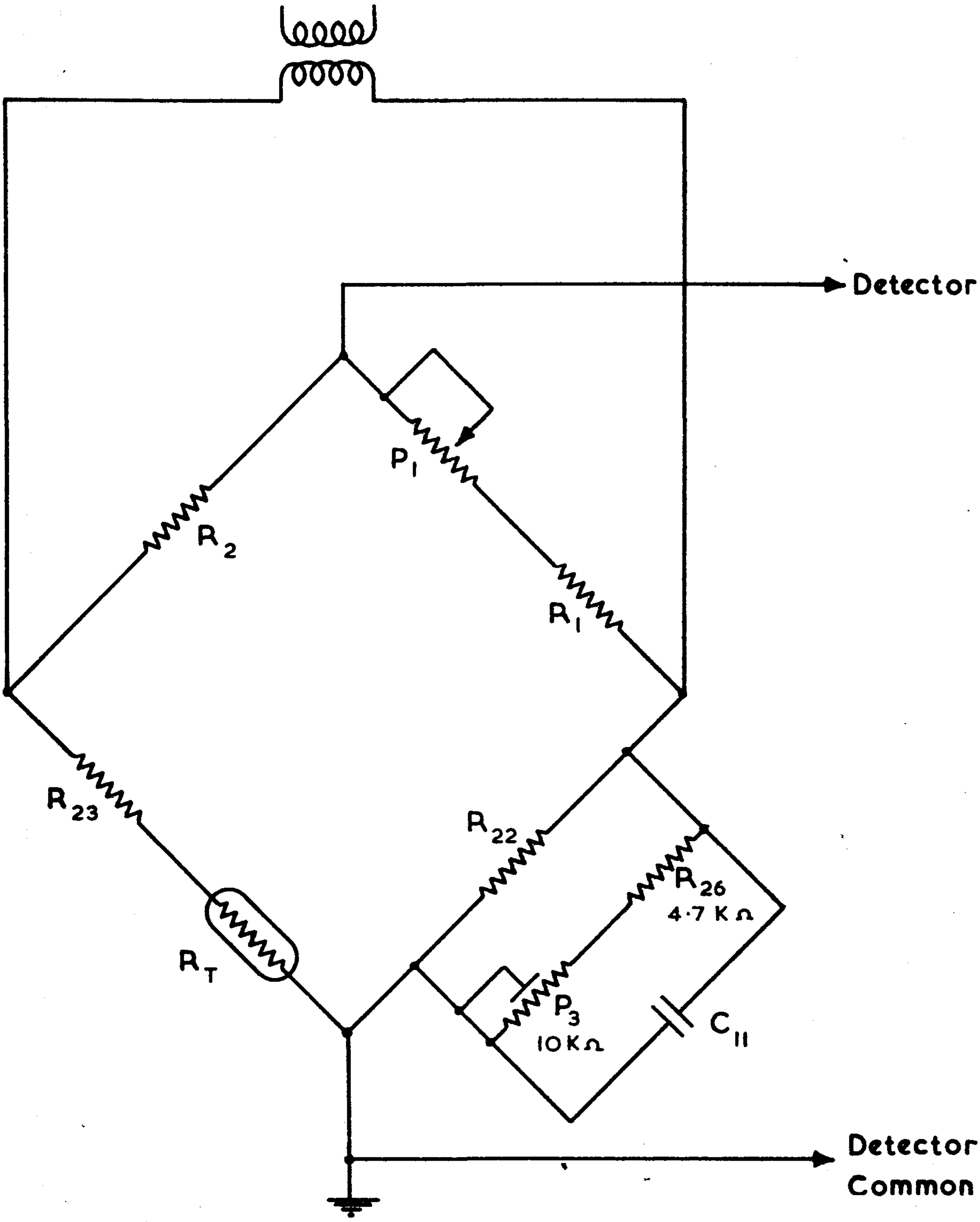
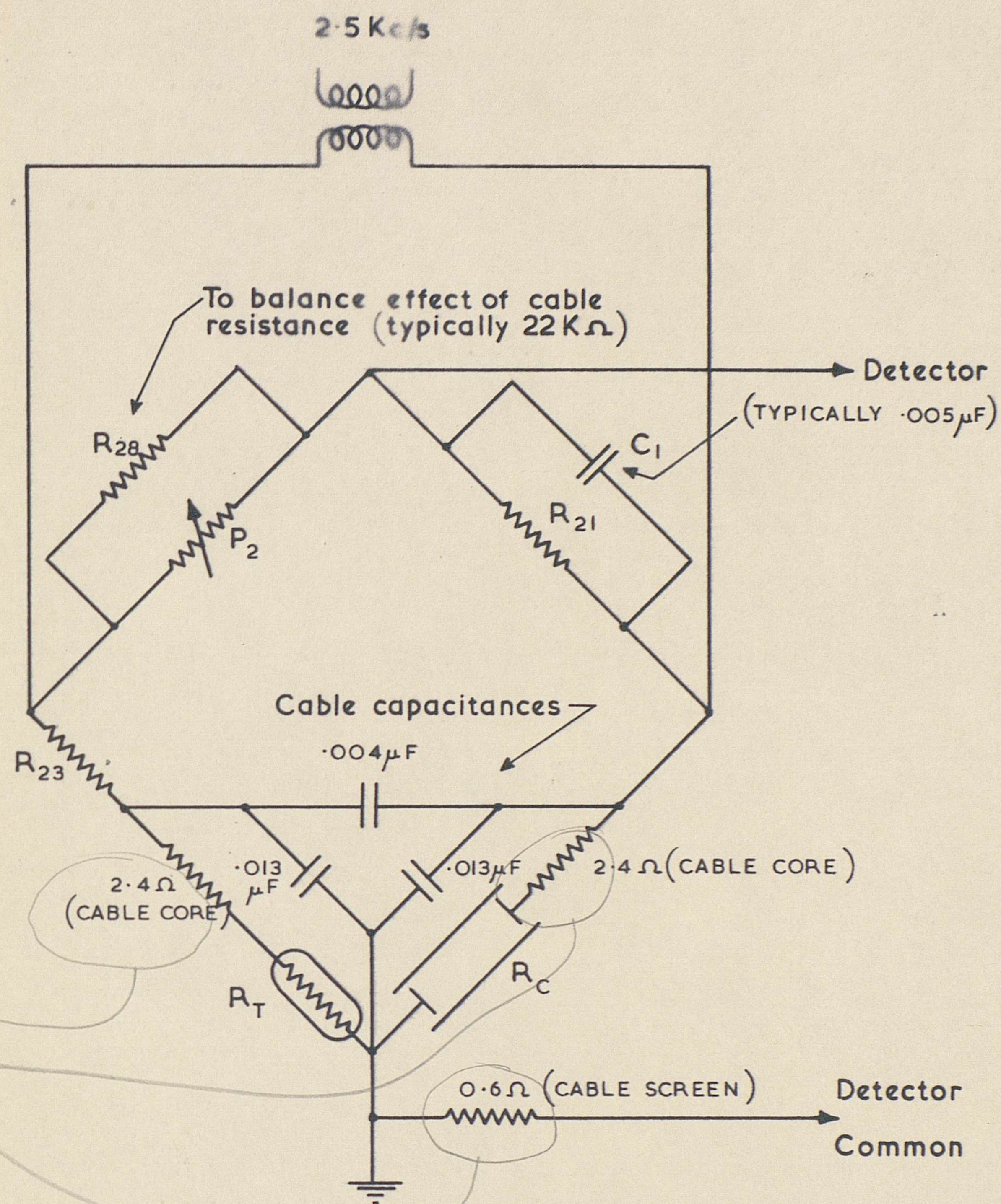


FIGURE 2

The temperature bridge with no appreciable cable impedances

Typical values not given in Fig 1. are :—

$R_1 = 220\,\Omega$ $R_2 = 390\,\Omega$ $R_{22} = 300\,\Omega$



4865/11 each of these 13Ω (on 300M. 4 core screen)

FIGURE 3

The salinity bridge with long cable (the trimming resistor and potentiometer and the alternative arrangement for P_2 have been omitted for the sake of simplicity.)

Typical values not marked here are given in Fig I

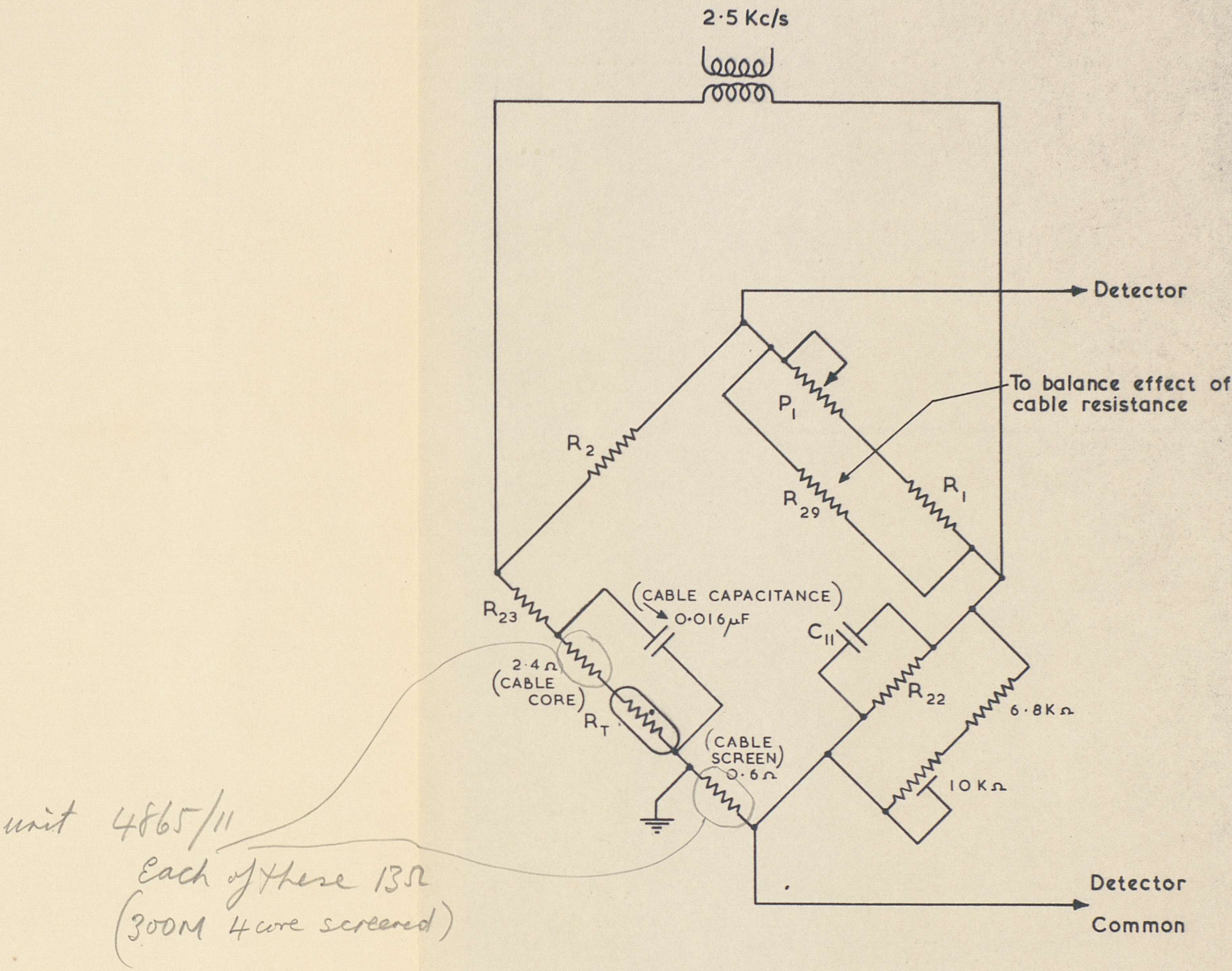
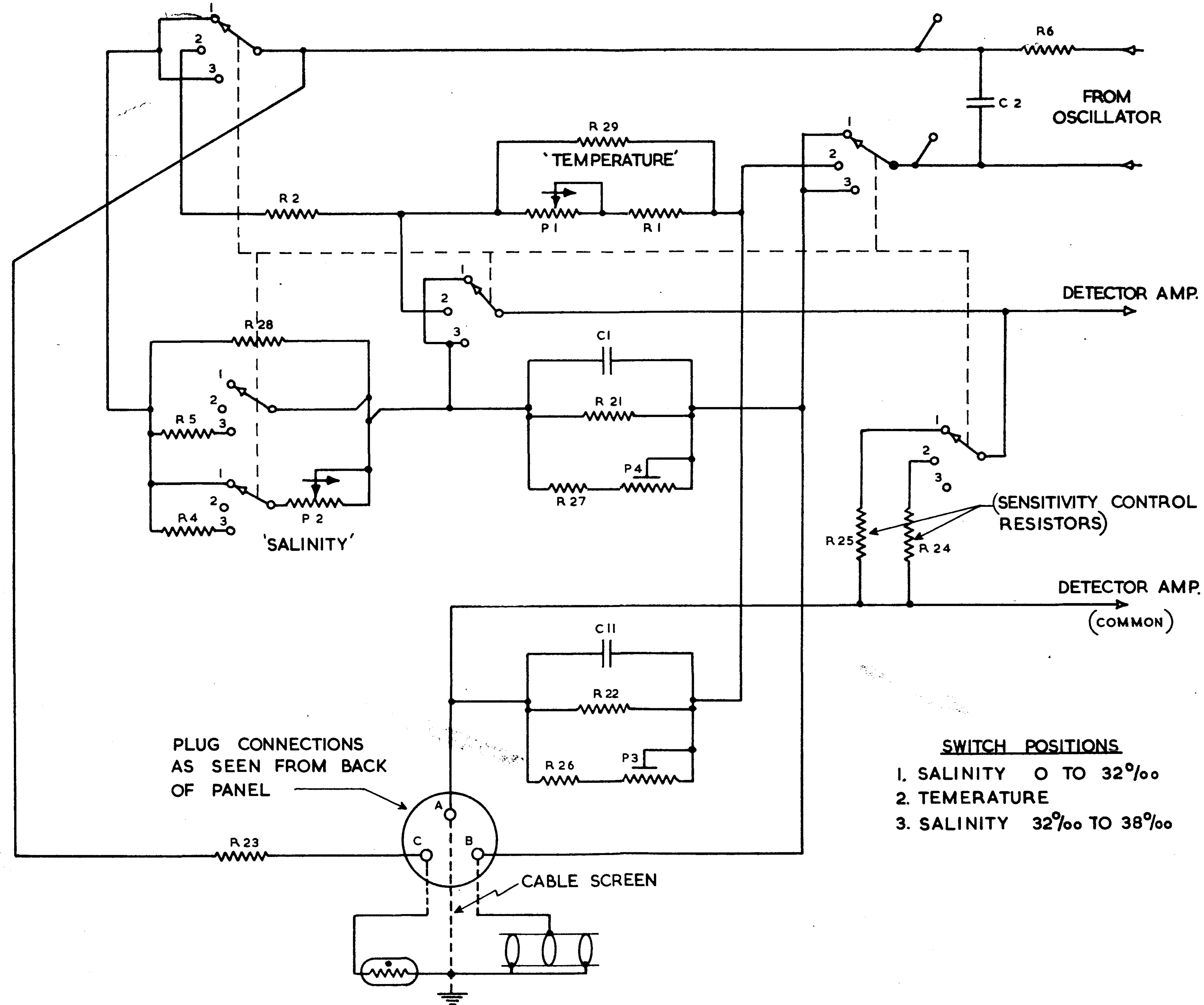


FIGURE 4

The temperature bridge with a longe cable

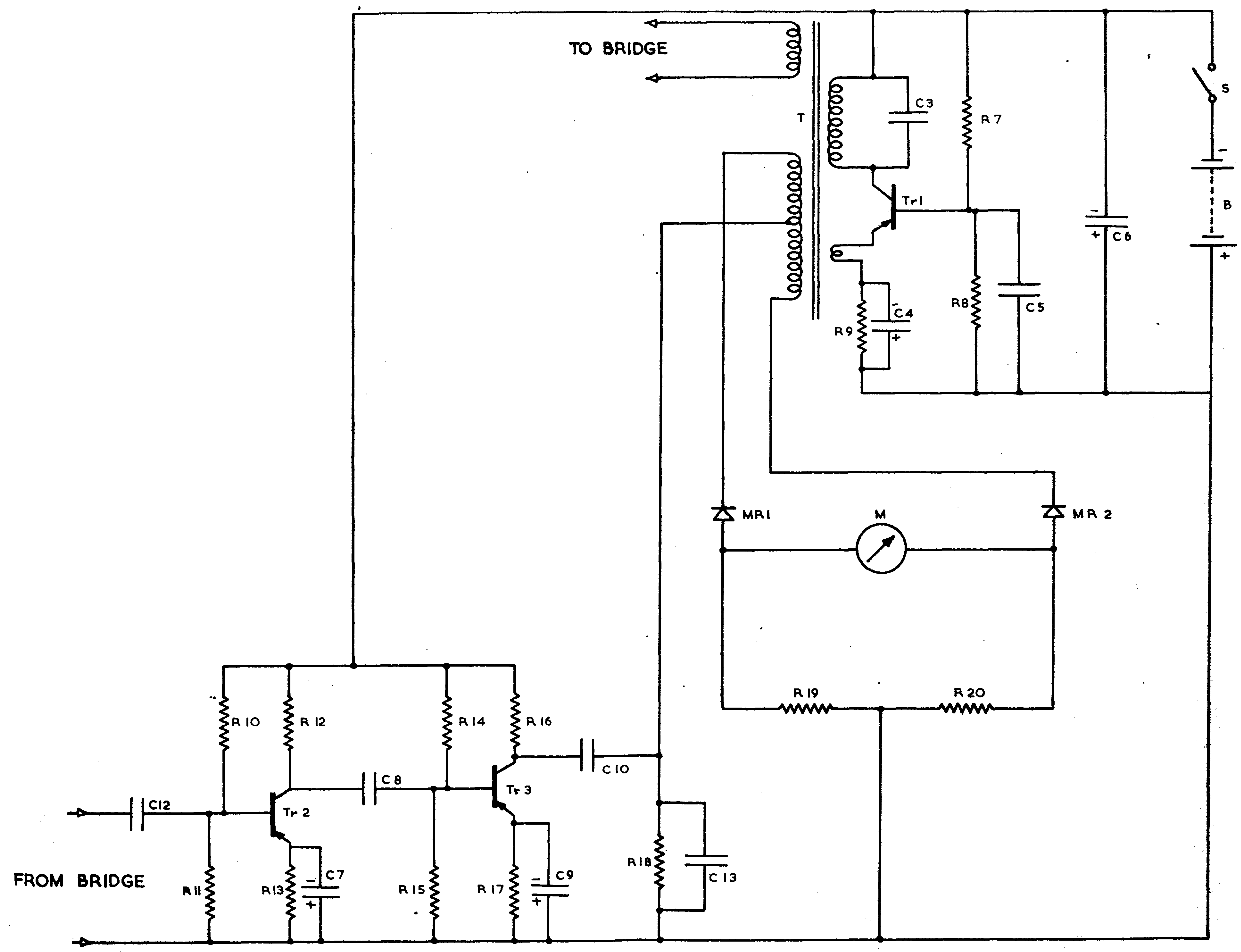
Typical values not quoted here are given in Fig 2



HAMON SALINITY-TEMPERATURE BRIDGE

N.I.O. 4865 SER. No.S 3 TO 8
BRIDGE CIRCUIT

NATIONAL INSTITUTE OF OCEANOGRAPHY. WORMLEY, SURREY.



HAMON SALINITY – TEMPERATURE BRIDGE

OSCILLATOR AND AMPLIFIER CIRCUIT

NATIONAL INSTITUTE OF OCEANOGRAPHY. WORMLEY, SURREY.