# Capacitance meter

## Measurement of capacitance in the 1pF-100μF range by the diode-pump principle.

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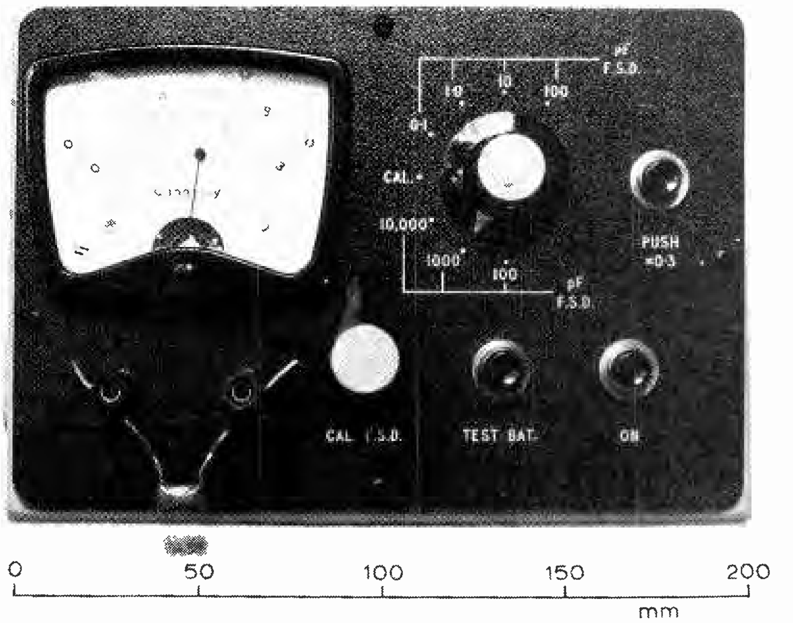
A direct reading capacitance meter is described which has no balance controls to adjust. The range covered is from 1 pF to 100 μF with an accuracy of about 0.5 pF plus 3%. The lowest range is 0-30 pF. The indicator is a 100 μA meter.

The circuit requires a 9V supply and is intended to be portable. The electronics are simple, one integrated circuit and five small transistors.




THE BULK of commercial capacitor measuring equipment is based upon the use of sinusoidal voltages with bridges. For investigating the quality of capacitors this is fine. But where just a simple capacitor size selection is involved the process is elaborate. The balancing tedium is reduced with automatic equipment, but this is expensive.

The capacitor is, of course, a component for storing charge, C=Q/V, (farads, amp-seconds and volts respectively) and it is possible to make direct measurement of stored charge per applied volt (farads) rather than use the capacitor's reactance which derives from charge modulation brought about by applying a sinusoidal voltage. Indeed, equipments are now appearing based upon this concept, such as injecting a constant current into the capacitor and measuring the time it takes to achieve a predetermined voltage. The larger the capacitor the longer the time, in a direct proportional relationship.

The equipment is well suited to the measurement of large capacitors which can be difficult to measure by the reactance technique. It can be built using digital techniques including a clock for the time measurement. Other techniques can also lead to the design of simple equipment.

If an upper limit for the capacitor size is set at about 100μF and a 100μA meter is suitable as a display, the capacitors can be measured using a repetitive charging technique which involves applying only a few volts to the capacitor, the value of which can be read from the meter in terms of the current flow. Even a capacitor as small as 30 pF will produce a 100 μA reading, provided the charge repetition is made high enough, in this case about 1 MHz.

The scale of the meter is linear and there is no need of special calibration. A wide range of capacitors can be catered for by making use of a few widely spaced frequencies and by altering the meter sensitivity using shunts. Readily achievable measurement errors are about 3% plus 0.5pF. Capacitors can be matched as accurately as the meter can be read, say to within 1% with a reasonable size of meter.

The basic circuit is that of the diode pump [1] and is shown in Fig 1, where the charging and discharging of the capacitor is accomplished with a square wave drive voltage. The charge and discharge currents are separated by diodes, so that only one of these flows through the meter. The circuit description is simplified by assuming the square wave has its lower level at 0V and upper at +V. When the voltage moves from 0V to +V the capacitor charges round the loop including diode $D_1$ and the meter.

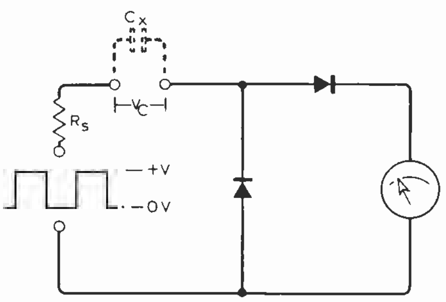



*Fig. 1. Diode pump principle*

The diode $D_2$ is nonconducting. It is intended that the capacitor obtains a substantially complete charge during this time. When the square wave returns to 0V the capacitor can discharge round the loop including $D_2$, with $D_1$ being nonconducting. The square wave input can be looked upon as a short circuit at this time since any current flow does not change the input voltage.

Thus, the meter has only the charging current flowing through it and the nature of a moving coil meter is to average the current flow. Current flow multiplied by time is charge and the current is therefore a measure of the size of the capacitor. It only remains to apply a suitable scale factor to allow for the number of volts being used and the number of times per second the capacitor is being charged. A capacitor able to deliver or absorb a current flow of one amp for one second while showing only a voltage change of one volt has a capacity of one farad.

By making the number of charges per second large the instrument will measure small capacitors. The large capacitors are charged less times per second in order to keep the current down to a manageable amount. But not so low as to cause excessive meter pointer jitter.

With capacitors as large as 100 μF the meter sensitivity had to be reduced to a full scale reading of about 2mA in order to comply.

The objective of the design is to have a linear scale and so the voltage change across the capacitor during charging and discharging must be independent of the particular size of capacitor being measured. Thus, a doubling in capacitor size must result in twice the charge. The resistance shown as $R_s$ in Fig. 1 must be small enough to ensure that even the largest capacitor can be charged to within a small percentage of completion within the time allowed by the square wave. The choice of square wave frequency is a matter for design and calibration and will be returned to later. But first some of the characteristics which are not of prime importance.

The square wave, for instance, need not be particularly square or have an equal mark-space ratio. But it should move between well defined voltage levels and have a flat top and bottom of sufficient extent to allow for substantially a full charge and discharge of the capacitor; 1% loss of charge voltage means a 1% low current reading. The square wave may have some ringing, say after changing from one level to the other, but must settle before the capacitor charge is complete to avoid over charging. The single polarity nature of the applied voltage will not be conducive to a mini-charge-discharge process during the ring unless the ring amplitude is very large. Finally the direct voltage associated with a square wave is not very important. Any d.c. is blocked by the capacitor after the first charge and plays no part in subsequent measurement. The d.c. level may need to be kept small however, to enable low voltage rated capacitors to be measured.

## Improved circuit

The circuit of Fig. 1 has the disadvantage that the meter is in the capacitor charging circuit and its series resistance or inductance could affect the accuracy of a measurement, particularly at high frequencies with small capacitors. The diode feeding the meter can be replaced with the emitter-base junction of a transistor and the meter transferred to the collector circuit, as shown in Fig. 2.

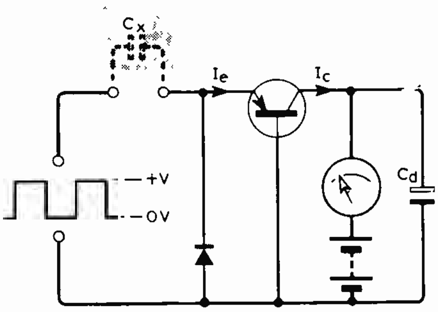



*Fig. 2. Transistor isolates the meter circuit from the capacitance*

Collector current is not quite equal to emitter current but with modern, high $h_{FE}$ transistors the difference is small and easily taken out in calibration:

$$I_c = I_e h_{FE}/(1+h_{FE}).$$

For instance if $h_{FE}$ is only 49 with collector current is only 2% less than the emitter and if $h_{FE}$ changes 10% with temperature the calibration error is a mere 0.2%. Clearly there are more important matters.

In Fig. 2 the collector is decoupled with $C_d$ which avoids effects due to meter coil inductance and Miller/Blumlein feedback reducing the transistor frequency response.

Also the circuit is tolerant of appreciable meter series resistance which means that the shunts which control the meter sensitivity can be made from convenient value resistors, as in Fig.3.

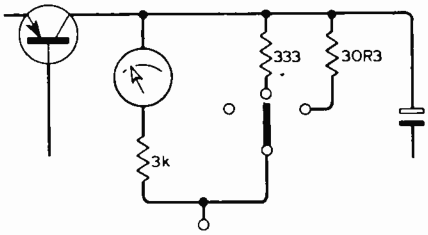



*Fig. 3. Meter sensitivity switching. Tolerance to meter resistance allows the use of shunts of reasonable values – in this case chosen to give 0.1, 1.0 and 10mA.*

The electrolytic decoupling capacitor $C_d$ needs a low leakage if the equipment is to be of the highest possible accuracy. For instance, if this were 2μA and the meter 100μA, then 2% of the meter reading may be time-dependent as the capacitor polarises. It is not difficult to find selected tantalum capacitors with a leakage current below 0.5μA in the size required.

**Square wave voltage.** Referring again to Fig. 1 it can be seen that the voltage drop across the diode $D_1$ reduces the amount of the square wave voltage applied to the capacitor and that across $D_2$ allows voltage to remain on the capacitor when it should ideally be discharged. However, as long as the required *voltage change* occurs across the capacitor, the measurement will be accurate and the square wave voltage can be increased to allow for the diodes. A voltage increase of 1 volt for the two silicon diodes is about correct since, if the equipment is being designed to be accurate, the capacitor must be substantially fully charged and discharged, and so the voltage increase required is that corresponding to a small diode current.

Another concern is that the voltage used to charge the capacitor shall be large enough to swamp any change in diode voltage with temperature. For indoor use the equipment is not likely to be subject to great temperature change and an allowance of ±20°C will be more than enough. Such a temperature range would cause a diode voltage change of about ±40 mV for each diode. Thus a square wave voltage of 4V pk-pk, plus another 1 volt for the diodes, should keep the effect of this upon calibration to 1% per diode. This 5 volts can be provided by a 9V transistor radio battery and is also small enough not to exceed the rating of most electrolytics. Thus the equipment should have a wide application.

**Square wave source resistance.** The square wave generator must be able to supply an adequate current to charge and discharge the capacitor in the time available, and this imposes constraints on the allowable source resistance. Assuming, in Fig. 1, that all the resistance can be lumped as $R_s$, the charge law is:

$$V_c = V_s(1-e^{-t/CR_s}) \quad \dots (1)$$

With an infinite charging time the term $e^{-t/CR_s}$ goes to zero and the capacitor voltage $V_c$ attains the voltage $V_s$. With a time $t$ equal to $4CR_s$ the term accounts for a 2% loss of charge. The capacitor will also not discharge by 2%. Thus compared to an infinite charging time there will be 4% less charge change and 4% lower current reading on the meter. If $C$ is reduced the error reduces, but the error is not linear and cannot therefore be compensated by simply increasing the voltage.

The equation can be used to examine whether $R_s$ is likely to be a cause of error in a completed equipment since the error with an increase in $C$ or $R_s$ grows rapidly; 2.7 times for a factor two increase in $C$ and 7 times if $C$ is increased four times.

The current flow through the meter in Fig. 1 is given by:

$$I = CVf \quad \dots (2)$$

where $I$ is in amps if $C$ is in farads, $V$ in volts and $f$ is the number of charges per second.

Assuming a 30 pF capacitor and a full scale reading of 100 μA, together with an effective square wave voltage of 4 volts, the frequency $f$ works out to be 833kHz. For a 100 μf capacitor the meter sensitivity must be reduced to avoid an absurdly low frequency. For 2mA the frequency required is 4 Hz, which is near to the lowest useable because of the need to smooth out needle jitter and still have a reasonable response time.

From equations 2 and 1 it can be shown that a large $I$ causes most difficulty with ensuring that the capacitor can be charged/discharged in the time available. If the values of $I$ and $V$ are made the same for each range the problem is much the same on all ranges. For instance the frequency must be decreased by a factor 10 each time the capacitor range is increased by a factor 10 and so the charge time constant $CR_s$, equation 2, always has the same relationship to $t$, i.e. $t/CR_s$ is fixed. In other words, the charge error is the same fractional amount on each range at the same meter reading, irrespective of the size of capacitor being measured, unless the meter sensitivity is changed. More current flows if $t$ is kept fixed and $C$ is increased but $t/CR_s$ is reduced (negative power) and the error increases.

In the equipment to be described the meter sensitivity is reduced to its lowest of 1.666 mA on the 100 μF range and so this range is chosen as an example of error due to inadequate charge time. The other ranges use 5 times less current and from equations 1 and 2 the error can be expected to be $e^5$ times less and will be negligible unless the 100 μF range is very poor.

From the equation 2 the average current required to charge a 100 μF capacitor once per second with an effective 4V supply is $I_{av} \times 10^{-4}$A. Since the meter is shunted to read 1.666mA, the frequency needs to be $1.666/10^{-4} \times 4)$ = 4.17 Hz, which has a half-cycle time of 0.12 seconds.

This range is for electrolytics which often have a tolerance of −20% +50% and precision measurement is not usually required. Thus a time of 4 $CR_s$ was deemed acceptable and means a 4% error at full scale, with less error at lower readings. From $4CR_s = 0.12$ it can be calculated that $R_s$ should not be more than 300 ohms and it will be seen later that the design achieves 330 ohms.

**Square wave generator.** The square wave voltage should be well defined in amplitude and change little in magnitude with temperature – an f.e.t. output stage is ideal. The LOCMOS integrated circuits have this type of output and the hex. inverter HEF4049 in particular has six stages, of which some can be connected in parallel to get a lower output resistance. Measurements on a few samples of these showed that a single stage had a typical output resistance of 1kΩ and thus three in parallel

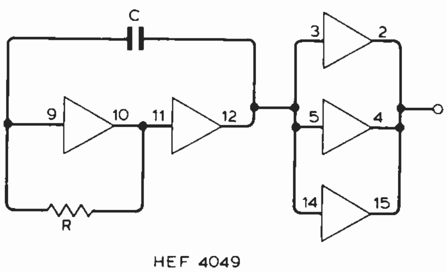



*Fig. 4. Five of the six inverters in the HEF 4049 i.c. used to generate square waves.*

would achieve, or nearly achieve, the target of 300 ohms. The connexion is shown in Fig. 4 and the square wave frequency is controlled by a single C and R and is easily changed to permit a number of different frequencies. Five of the stages are used and the sixth is put to a use which will be seen later.

THE author, Ken Holford, is a principal engineer with Philips (previously Mullard) Research Laboratories and has been involved in circuit design for about 20 years. His electrical engineering started just after the 1939-1945 war, when equipment was in short supply. Power supply failures were common, your own generator a luxurious necessity, and a permit required for a new electric motor. He joined a Midland engineering company rewinding and redesigning equipment, often war surplus having the wrong voltage rating. He obtained an HNC from evening studies and moved to the research and development lab. of a motor vehicle component manufacturer.

Having an interest in electronics he joined Mullard and studied semiconductor circuit design. By 1960 such knowledge was in great demand and he teamed up with colleagues to lecture other Mullard engineers, extending this activity to many surrounding colleges. He was a contributor to the book "Reference Manual of Transistor Circuit Design" (1960) which was produced in thousands by Mullard at that time.

More recently, in September, 1972, he wrote a "Doppler with-sense" microwave article for *Wireless World*. He designed the Mullard microwave vehicle detector of the automatic portable traffic signals used at road-work sites in the UK.

The capacity meter was a hobby project.

This does the job although, due to the input stage not being of the high gain op-amp type with an accurate threshold at half supply voltage the square wave mark/space ratio is up to 20% different from unity. The circuit produces a respectable square wave at frequencies up to 1 MHz, as shown in Fig 5.

Earlier, the designer had considered using a modern f.e.t. op.-amp., such as the RCA CA3130, but this did not have the frequency response to produce a satisfactory square wave at 1 MHz. It would also need an output stage buffer. The 555 was also a possibility but a need for two timing resistors was a disadvantage. No doubt other i.cs could be found to do a similar job, or perhaps better. But as this circuit proved adequate and, as time was not unlimited, the design was frozen.

In a battery-powered measuring equipment used casually, the greatest loss of battery power is caused by the instrument being inadvertently left on. One way of avoiding this is to dispense with the normal switch and have a push button which activates the circuit for a

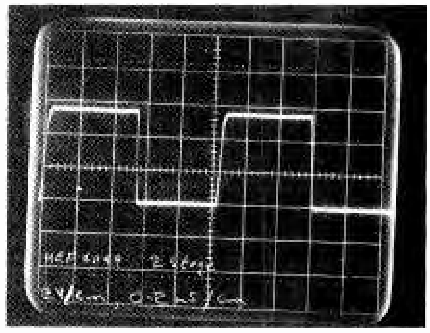
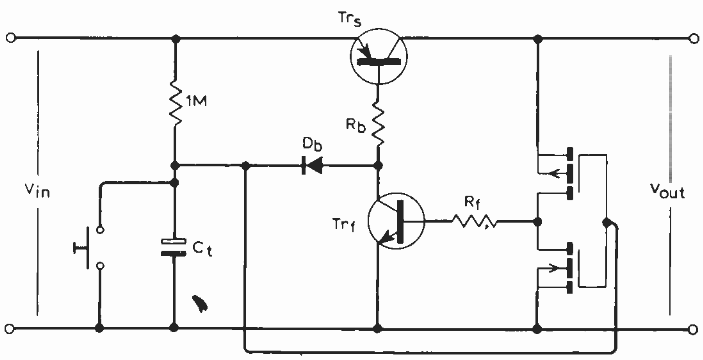


*Fig. 5. Output waveform of circuit of Fig. 4. Oscilloscope sensitivity 2V/cm, timebase speed 200ns/cm. In this case timing resistor was 4.7kΩ and capacitor 68pF.*

*Fig. 6. Power supply switching and timing circuit. Inverter is part of HEF 4049.*



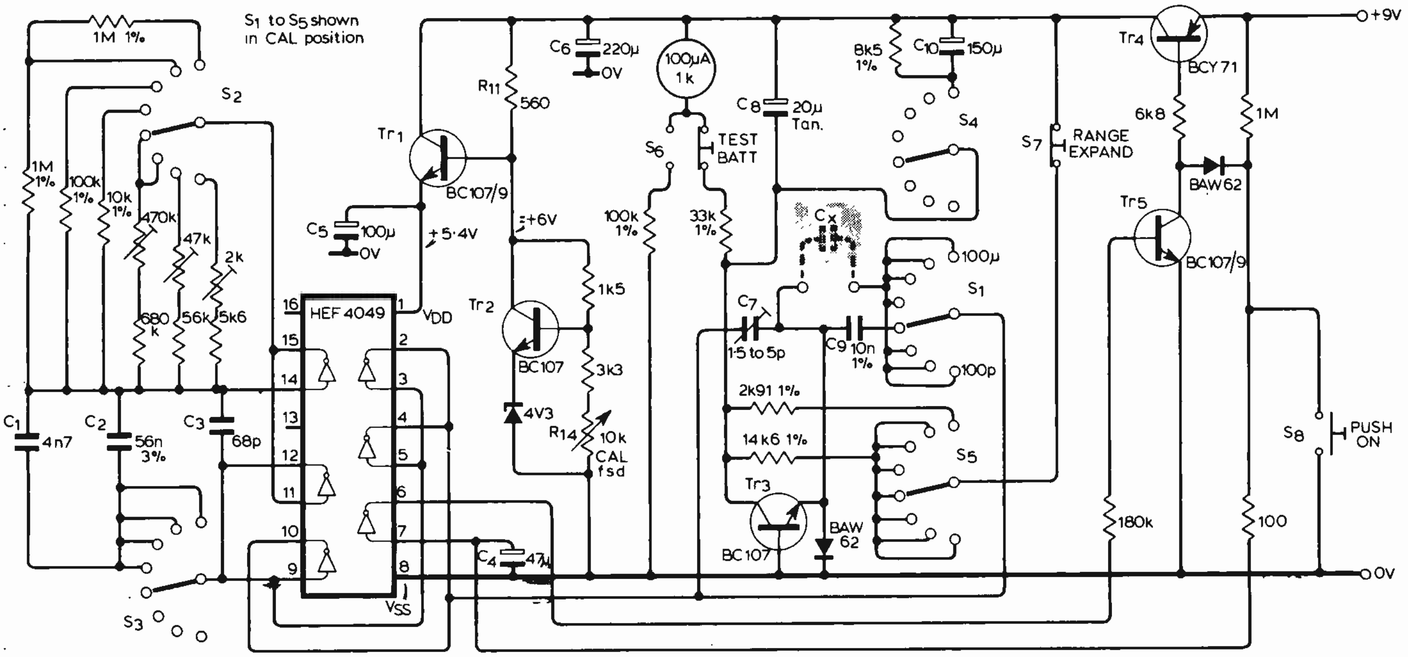



*Fig. 7. Complete circuit diagram. Capacitor $C_8$ should not exhibit more than 1μA leakage and the voltage supply must not fall below 7A.*

fixed time. If more time is required the button can be re-pressed to extend the period. The use of f.e.ts makes this easy. A measurement can easily be completed in 15 seconds and a timer was made for 30 seconds. One of the LOCMOS stages was used for this and the basic principle is shown in Fig. 6.

Normally $C_t$ is charged and the output voltage of the circuit is zero because the series transistor is off. Pressing the push discharges $C_t$ and turns on the series transistor $T_s$ by allowing current to flow through $R_b$ and $D_b$. The input voltage $V_{in}$ is then applied to the f.e.t. inverter $T_i$, the gates of which are now low and their centre at substantially supply line voltage. This centre supplies votage to $T_f$ base and $T_f$ in turn supplies transistor $T_s$. Upon release of the push the capacitor starts to recharge and when the voltage gets to about half the $V_{out}$ supply voltage the supply to $R_f$ is reduced and the circuit shuts down. Since $C_t$ remains charged in the off condition it is kept well polarised and the leakage current should be low. Any leakage is not significant in affecting battery life, only timing.

## Complete circuit

The complete circuit is shown in Fig. 7 and has seven capacitor ranges increasing from 100 pF to 100 μF for a full-scale meter reading. On one further position a 1% tolerance capacitor is switched in so that the 100 μA calibration can be checked and rest if necessary. A push button will remove a meter shunt so that any range can be expanded from 0-100 to 0-30. Thus, except for capacitors of less than 10 pF, no capacitor need be measured such that the reading is below 0.3 of full scale. The meter is scaled 0-30 and 0-100.

Before describing the complete circuit further it is worth listing the functions of the various switches which have been numbered for this purpose.

$S_1$ Connects a calibration capacitor across terminals and disconnects the unknown.
$S_2$ Selects the frequency timing resistor for the square wave.
$S_3$ Selects one of two timing capacitors for the square wave.
$S_4$ Changes the meter shunt and the size of smoothing capacitor on the 100 μF range.
$S_5$ Selects the value of the meter shunt which will be removed when the range expansion button is pressed. This is different on the 100 μF range to that on the others.
Note that $S_1$ to $S_5$ are 1-pole, 8-way switches.
$S_6$ Battery test single-pole, changeover push button.
$S_7$ Range-expand single-pole, normally-closed push button.
$S_8$ "Switch-on" single-pole, normally-open push button.

Most of the circuit will be recognised from the previous description. $Tr_4$ is the series switch, turned on by $Tr_5$, which itself is turned on by the output at terminal 6 of the hex. inverter when the push button $S_8$ discharges $C_4$.

The voltage supplied to the hex. inverter controls the magnitude of the square wave and in turn the magnitude of the meter current reading for a given capacitor size. The method of setting the calibration is to adjust this voltage by $R_{14}$.

The regulator, $Tr_1$ and $Tr_2$ is simple but sufficient because of the use of a built-in precision capacitor which enables the calibration to be checked and reset if necessary. $Tr_1$ is an emitter follower which transfers the voltage from $Tr_2$ collector which, in turn, is set by $R_{14}$. Only about 0.6V is lost across $R_{11}$ when the battery voltage is low in order to conserve battery life.

The oscillator frequency is determined by the value of *R* and C selected by $S_2$ and $S_3$. On the four highest capacity ranges the resistors should have a tolerance of 1% and, as can be seen, are fixed. Calibration is made correct using the CAL control using a precision capacitor in the test position. Afterwards the voltage at terminal 1 of the i.c. should be measured and, if it is not 5.4V ±0.2V, the capacitor $C_2$ is probably not quite correct. If voltage is high, the battery life will be shortened, since at design centre a minimum voltage of 7V is recommended and the battery starts with 9V.

On the other ranges, the value of the timing resistor is adjustable and so each range can be set as accurately as the standards available for calibration. The CAL range and the 0.01μF range are common, so setting the CAL using the instrument's own internal standard should be sufficient. On the 100 pF range, the trimmer $C_7$ across the measuring terminals will need adjustment — best done with the range expand in use. The best setting was found to be that which caused a reading of 0.3 pF with nothing being measured. The measuring error was then not more than 0.5 pF anywhere on the range. With no $C_7$ the error was 2pF.

The battery timer is set for about thirty seconds, depending a little on leakage currents. This can be extended if required, or the push button omitted and a normal on-off switch used. The advantage of the push button is that battery life can be more than 12 months with the equipment in casual use.

**Reference**

1. A thorough explanation of the circuit is given in "The diode-transistor pump," by D.E. O'N. Waddington, *Wi eless World*, July 1966, p.338.