Direct-voltage references

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Abstract

Precise sources of e.m.f have existed mainly in three forms : the electrolytic cell, the gas-discharge tube and the avalanche or Zener diode. The paper attempts to place these various voltage-reference devices in historical and technical perspective. The properties of several types of cell are given, followed by a similar treatment of glow-discharge and corona-discharge tubes and finally a rather fuller account of the Zener diode and other solid-state elements. The relative merits of all these reference devices are then discussed. The paper concludes with an outline of some of the latest techniques for the successful use of these devices. The list of papers to which reference is made includes most of the original texts.

List of principal symbols

r_z = incremental resistance of Zener diode at specified breakdown current
I_R = reverse (breakdown) current of Zener diode
V_z = breakdown voltage of Zener diode
v_n^2 = mean-square-noise voltage
k = Boltzmann's constant
T = junction temperature, K
f = bandwidth, Hz
r_D = incremental resistance of forward-biased diode
V_D = forward voltage drop across diode
I_D = forward current in diode or drain current in field-effect transistor
q = electronic charge
V_{BE} = base-emitter voltage in bipolar transistor
I_E = emitter current
I_{EO} = reverse saturation current of base-emitter junction
V_R = reference voltage
E_G = energy gap
V_o = output voltage of amplifier or system
V_{11} = input voltage to noninverting input terminal (terminal 1)
V_{12} = input to inverting input terminal (terminal 2)
A = voltage gain of amplifier
V_{os} = input voltage offset
I_1 = direct current into input 1
I_2 = direct current into input 2
R_s = source resistance
R_f = resistance of feedback path
I_{os} = input offset current
R_{os} = offset resistance

1 Introduction

The term 'voltage reference' is widely used to describe a stable source of e.m.f. which forms part of a measuring system, and is the local standard by means of which the measurement is made possible. Voltage references are an integral part of the majority of electronic measuring instruments of the present day; hence their importance.

A voltage reference differs from a 'voltage standard' in that it does not usually constitute a precise source of an absolute value although, if it is sufficiently stable, it could do. Nor does it require the careful handling and method of application of a voltage standard; it is altogether a more robust device. The word 'reference' itself suggests that one is dealing with something which is part of a portable or mobile system and is the most trustworthy part of that system as far as calibration is concerned.

Owing to the enormous improvement in the sensitivity and stability of electronic amplifiers over the last 25 years, it is now possible to use relatively delicate voltage sources such as the Weston standard cell for reference purposes, subject perhaps to the main limitation that such cells should not be moved about prior to use. It will therefore be relevant to discuss these and other voltaic sources in this paper, and to discuss the electronic-circuit techniques required in their use.

During the last 40 years, research has been directed towards replacing the original voltaic type of reference by a 'passive' device such as a gas-discharge tube or its solid-state equivalent – the Zener diode. The discharge tube reached a considerable standard of perfection in the postwar era, although it has now largely disappeared from use, at least in new equipment.

The solid-state reference, however, has gone from strength to strength and now offers a serious challenge to the standard cell.[1] It is with this type of reference that the present paper is chiefly concerned, but it will be valuable to place it in historical and technical perspective by means of the survey which follows. It should be borne in mind that the Zener diode is not always the most convenient device for reference purposes, and it is therefore worthwhile to review the alternatives.

2 Electrolytic cells as voltage references

Benson[2] has given a good account of the characteristics of many types of cell. For the present and foreseeable future, only three types are likely to be important as primary references. They are as follows:

(*a*) the Weston cell
(*b*) the dry battery (zinc–carbon Leclanché cell)
(*c*) the mercury cell.

2.1 Weston standard cell

The Weston cadmium cell has been known for more than half a century. It is in use throughout the world as a primary standard, although it is now possible to make an absolute evaluation of the standard cell by means of the Josephson effect.[3] Full information on all aspects of this cell is obtainable from the US National Bureau of Standards.[4] Many companies offer cells in single units or batteries mounted in enclosures, maintained at constant temperature, sometimes with suitable protective electronic circuits. Using temperature control to better than 0·01° C, a stability of 1 part in 10^6 per day (1μV) is frequently claimed.[5,6]

Because of the high internal resistance of the Weston cell, typically about 1000 Ω, it is not possible to obtain precision or stability unless the current drawn from the cell is less than 10^{-9} A. It is important to avoid overloading the cell, even temporarily, e.g. by out-of-balance conditions that may exist before an apparatus is fully warmed up. For instance after a short circuit it may be several hours before the cell will again give satisfactory service.[2]

Two types of cadmium cell are commercially available:[7] (i) the saturated type, used whenever a reproducible absolute value of e.m.f. is required and some temperature control is available; (ii) the unsaturated type which has a very low temperature coefficient, typically 3 parts in 10^6/degC.

2.2 Leclanché cell

Dry batteries have been widely used as references because of their cheapness and the fact that so many different combinations of voltage and capacity are available. In equipment which employs vacuum tube amplifiers, it is usually necessary to use high-voltage references, 45 or 90 V being favourite values. Compact batteries of such voltages were at one time freely available from retailers. However, the disappearance of radio valves from domestic equipment has affected this situation adversely; in ten years time it may not be possible to obtain batteries with voltages in excess of 12 V. Nevertheless the ease with which dry cells and batteries can be connected together to form any desired multiple of 1·5 V renders them an attractive choice for use in certain kinds of research or laboratory equipment, since the designer is able to specify a voltage reference of the required value and to choose the best two points in the circuit across which to connect it.

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Although dry batteries have a much larger temperature coefficient than either the Weston cell or the mercury cell, their physical size often renders them sufficiently temperature stable over the short term. They have a low internal resistance and sufficient capacity to provide up to 1 μA of current drain without loss of stability or life. Patchett[8] quotes a long-term (14 months) stability of 1% for a 9 V battery consisting of cylindrical cells, and it appears[9] that 0·05% over several months is obtainable. Even better results are possible with layer batteries,* which offer longer shelf life than batteries of similar size formed from cylindrical cells. In temperate climates, such batteries give good service over a period of 2–3 years.

2.3 Mercury cells

These were originally developed as high-power sources for portable equipment. They have particularly low internal resistance and have a low temperature coefficient. They are somewhat more expensive than zinc–carbon dry cells and are not, in general, available from retailers. A recent paper[10] describes the use of such a cell as the reference in a 1 A current stabiliser for which a stability of 1 part in 10^6 per hour is claimed. Mercury cells are particularly suitable for applications requiring a reference of small physical size.

Table 1
CHARACTERISTICS OF SOME ELECTROLYTIC CELLS

	Nominal e.m.f.	Temperature coefficient	Internal resistance	Shelf life
	V	μV/deg C	Ω	years
Unsaturated Weston cell	1·0193	5	1000	10
Leclanché cell	1.5	− 400	1–5	2–3
Mercury cell	1·35	+ 25	0·5–2	2–3

2.4 Comparison of electrolytic cells

The principle characteristics of the three types of cell are listed and compared in Table 1. There is little or no information about the noise output from cells. The author has made measurements over the years on various types of reference cell which lead to the conclusion that, for a cell in good condition, the noise is largely the thermal noise associated with the internal resistance. In any event, it is usually quite practicable to reduce a.c. interference by restricting the bandwidth of the amplifiers used to buffer the reference.[5]

3 Discharge-type references

These are of two kinds, the glow discharge and the corona discharge. Neither are much used nowadays, although corona tubes are useful for providing very-high-voltage references where there is no solid-state equivalent.

3.1 Glow-discharge references

The nonlinear conduction properties of ionised gas have been known since the work of Townsend and Hurst[11] at the beginning of the century. The principle of voltage stabilisation by this means is explained by Benson.[2] A thorough examination of early examples of commercial tubes such as the 7475 and 85A1 was made in the postwar years[12,13] to be followed later by a similar study of the celebrated 85A2 and other miniature tubes.[14] Most of these tubes are now out of production, although the more recent types are still freely available for replacement purposes. The most recent tube to appear is the 83A1 for which the manufacturers publish a great deal of data.[15] The data in Table 2 are typical and will serve as a basis for the comparison of references in Section 5.

Gas-filled tubes are subject to hysteresis and random discontinuities in their I/V characteristics. This implies that an individual tube may show variations in its running voltage between successive periods of use, i.e. when it is extinguished and then restruck. These variations are frequently of several volts in magnitude.[2] Therein lies perhaps the greatest weakness of this type of reference. Nevertheless it is remarkable to what state of perfection these reference tubes have been developed; the short-term stability obtainable under steady running conditions is said to be 0·01% over a period of 8 h.[15]

It is possible that glow-discharge devices may still be considered advantageous as high-voltage references when compared with Zener diodes of the same stabilising voltage, particularly with regard to temperature coefficient and power requirement. They are not prone to catastrophic failure as are solid-state devices, but they will suffer a gradual deterioration in performance when subjected to occasional overload.

Table 2
CHARACTERISTICS OF THE 83A1 REFERENCE TUBE

Nominal burning voltage, V	83
Maximum variation from tube to tube	83–84·5
Average temperature coefficient, μV/deg C	− 30
Incremental resistance, Ω	110–350
Typical noise (30 Hz–10 kHz), μVr.m.s	100
Preferred running current, mA	4·5
Life expectancy, h	10 000
Probable change in burning voltage during lifetime, %	1·0

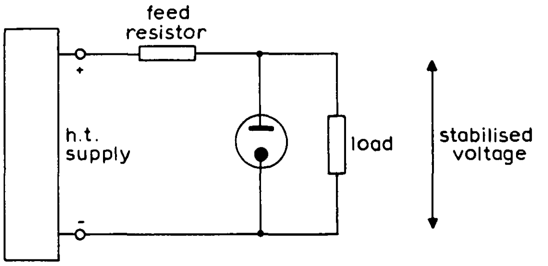

Fig. 1
Principle of voltage stabilisation using a corona-discharge tube

3.2 Corona-discharge tubes

These tubes cater for reference voltages of 350 V or more. Commercial versions up to 16 kV are currently available.* It is probably wrong to regard them as voltage references, since they are unlikely to be used in conjunction with amplifiers as part of a feedback-comparison system, but rather as simple regulators in their own right, as is shown in Fig.1. This is simply a stabilising application, the tube attempting to maintain a constant running voltage despite small changes in either the input voltage or the load current. If changes in loading are very small, however, we can regard the device as having the function of a reference, particularly if the gross changes in input voltage are removed by some preregulation, as shown in Fig.2. When the device is used in such a way, a stability of 1% per 1000 h is typical, and a temperature coefficient of 0·02%/deg C is claimed.[2] Tube noise seems to be several orders higher than in glow-discharge tubes,[16,17] but this is unlikely to be important in normal applications since one is thinking here of a comparatively crude reference. Corona tubes have a high incremental resistance, typically 250 kΩ. There may be some scope in specialised applications for the adoption of a precorona discharge as originally suggested by Brown[18] for use as a voltage reference.

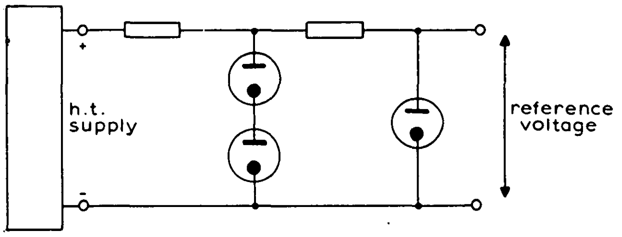

Fig.2.
Method of cascade stabilisation, here applied to corona-discharge stabilising tubes

A range of miniature tubes of much improved performance is now available under the brand name 'Corotron'. Typical figures for the 1000 V version are: tolerance ± 1·5%, internal resistance 50 kΩ nominal running current 100 μA, temperature coefficient 0·009%/deg C.

4 Solid-state reference devices

4.1 Breakdown devices

Following on the development of the p–n junction, the phenomenon of reverse breakdown was extensively examined.[19,20]

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* Ever Ready PP9 etc.

* M-O Valve Company Ltd., Brook Green Hammersmith, London W.6

Junction diodes used for their breakdown properties were at first known to many as 'breakdown diodes' and subsequently as 'Zener diodes' on account of the early work of Zener,[21] on whose theory the breakdown phenomenon was thought to depend. Garside and Harvey[22] refer to the further development of the field-emission and avalanche-breakdown theories, which are now accepted as the basis for the behaviour of these diodes.

As semiconductor technology developed, it rapidly became clear that, with suitable semiconductor doping, a class of diodes with a sharp, predictable breakdown region could be fabricated, and that these would form extremely useful circuit elements, both as regulators and as references. Throughout this paper the term 'Zener diode' will be used for such devices.

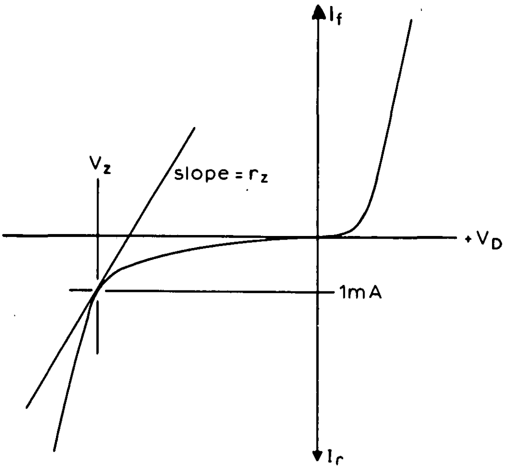

Fig. 3
I/V characteristics for a typical Zener diode

A good account of the characteristics of Zener diodes is given by Garside and Harvey,[22] and by Waddell and Coleman.[23] The essential shape of the I/V characteristic may be seen in Fig. 3. It will be observed that the reverse current increases rapidly when a certain voltage V_z is reached. A practical minimum value for the current threshold is 1 mA, and, if the slope of the tangent to the curve is evaluated at this current, we obtain a value for the incremental resistance r_z. (Some manufacturers quote a value for r_z at I_R = 5 mA or some other appropriate current.) Although the value of r_z is mainly of importance when the diode is used as a regulator rather than a reference, it is an advantage to arrange that it is as low as possible, low enough in many cases to be neglected in calculations of stability. r_z is roughly proportional to the reciprocal of the working current through the junction (i.e. I_R), and its precise value depends on junction area, doping levels and junction temperature. An important observable fact is that, other things being equal, r_z has a very pronounced relation to the Zener voltage V_z as is shown by the graph of Fig. 4. It reaches a shallow minimum for diodes for which $V_z \approx 7$ V.

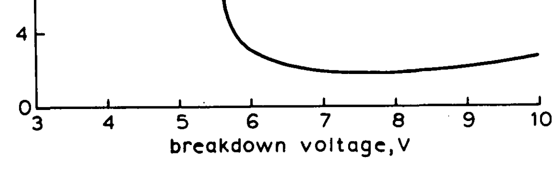

Fig. 4
r_z/breakdown-voltage curve

Perhaps the most interesting and useful feature of Zener diodes is the possibility of obtaining a near-zero value of temperature coefficient by suitable choice of breakdown voltage. Diodes which break down at less than 4·5 V have a pronounced negative coefficient, said to be due to field emission,[24] whereas for $V_z > 6{\cdot}5$ V the breakdown is due to avalanche effects,[20] and a positive coefficient results. Between 4·5 and 6·5 V both mechanisms exist, and for certain values of V_z within this range (depending on environmental factors) the temperature coefficient is very small. Fig. 5 shows the form of the temperature coefficient for a range of breakdown voltages. For normal working currents, say around 5 mA, the 'zero point' lies somewhere between manufacturers' preferred values, namely between 5·1 and 5·6 V. It must be remembered, however, that the temperature coefficient is a function of the working current, a fact which enables the coefficient of a given diode to be varied to some extent. The author has found that a diode with a nominal breakdown voltage of 5·6 V at I_R = 20 mA gives a near-zero coefficient when operated at 6 mA, facts which seem to agree with the results of Garside and Harvey. Zener diodes suitable for use as references are the small glass-encapsulated variety, having a maximum dissipation of 400 mW.

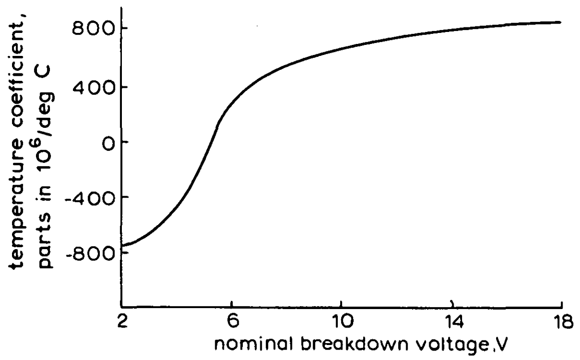

Fig. 5
Relation between breakdown voltage and temperature coefficient

For many years it has been possible to buy suitably selected or adjusted reference devices based on Zener diodes intended for high-stability applications. Many of these devices have been multiple encapsulations consisting of a positive-temperature-coefficient Zener diode in series with a negative-coefficient, forward-biased diode or transistor. Extremely good performance is claimed, but there is very little freedom of choice as to the reference voltage offered, or the working current to be used. A typical specification is:*

V_z stable to 0·01% ± 5 parts in 10^6/deg C from −55 °C to 125 °C
stability, 5 parts in 10^6 over 24 h
load variation not to exceed ± 3 nA.

One drawback with powered references is self heating. For a 5·6 V diode, operated at 6 mA, one can expect a rise in junction temperature of 5–10 °C depending upon mounting arrangements. Therefore, with the best diodes obtainable, the warm-up drift is not likely to be less than 25 parts in 10^6. The possibility of operating diodes at much lower currents is therefore attractive, and has been considered by at least one manufacturer.† If it is desired to operate at 100 μA for example, a diode with a breakdown voltage of 7·5 V at 5 mA is suitable and has a running voltage of 6·7 at I_R = 100 μA. Under such conditions, the incremental resistance is high, of the order of 1000 Ω, and the noise output may become troublesome. Zener diodes exhibit a wide range of noise output, even among diodes of the same nominal voltage, operated under the same conditions. One would expect a mean-square-noise voltage of at least

$$\overline{v_n^2} = 4kTr_z\,\Delta f \qquad (1)$$

It is unlikely that the variations of noise mentioned above are attributable solely to differing values of r_z (which arise because of variations in the quality of the p–n junction[22]), although the noise is certainly reduced when r_z is decreased by working at a larger breakdown current. Noise levels of up to 100 times the Johnson noise given above are well below 1 part in 10^6 of the Zener voltage, however, if the bandwidth is restricted to 10 Hz.

Although Zener diodes are currently available with breakdown voltages of from 2 to 200 V, only the 5–8 V types should be considered for reference purposes. Higher values of reference voltage can conveniently be achieved either by feedback methods or by stacking several diodes in series, as has been the regular practice with glow-discharge tubes. On the other hand, where very low reference voltages are required, particularly where battery power supplies are in use and the supply voltage is limited, it may not be possible to use Zener diodes. In such cases, special circuit techniques are called for (Section 6).

4.2 Forward-biased diode

A forward-biased p–n junction has some crude stabilising

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* Motorola Semiconductor Products Inc, Phoenix, Ariz., USA
† SGS-ATES (UK) Ltd., Planar House, Walton Street, Aylesbury, Bucks., England

properties in that its incremental resistance is small compared to its effective d.c. resistance. In a silicon junction, for example, a forward current of 1 mA establishes a forward voltage of about 650 mV; a 1% change in the current will give rise to a change of about 0·25 mV across the junction, since the incremental resistance r_D is about 25 Ω as derived from the well known relation

$$r_D = dV_D/dI_D = kT/qI_D \tag{2}$$

The voltage stability of such an arrangement is therefore good, provided that the junction temperature can be kept constant. The circuit arrangement is shown in Fig. 6a. Better results are obtained if a transistor is used as in Fig. 6b, since, in this case, the ohmic resistance of the diode is less important.

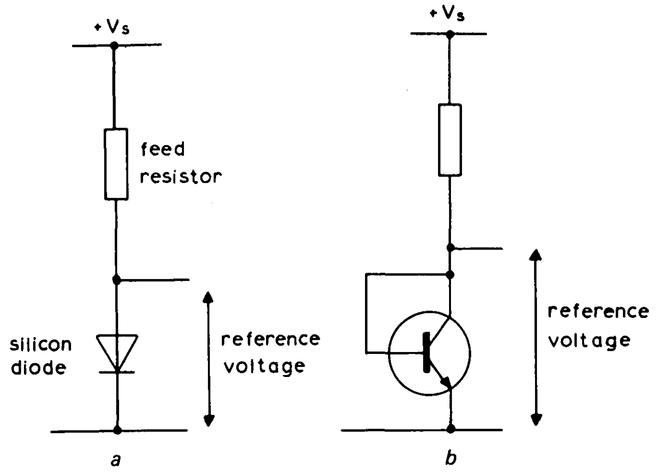

Fig. 6 *Diode and transistor as voltage and diode reference, respectively*

a Use of a forward-biased diode as a voltage reference
b Use of a transistor as diode reference

The temperature coefficient can be found from the well known relation for a transistor

$$V_{BE} = kT/q \log_e \{I_E + I_{EO}/I_{EO}\} \tag{3}$$

by differentiation[25] to obtain

$$dV_R/dT \simeq (V_{BE} - E_G)/T \tag{4}$$

The coefficient turns out to be −2 mV/deg C over a wide range of current, a rather high value. Nevertheless, the configuration of Fig. 6b is widely used in monolithic circuits for the establishment of a local voltage offset – a kind of crude reference in some respects.

4.3 Field-effect transistor as a reference device

The very high slope resistance of a junction field-effect transistor or f.e.t. when operated beyond pinch off is well known.[26] Indeed, the simple theory predicts that the drain current I_D is independent of the drain-to-source voltage V_{DS} beyond pinch off. It has, however, a temperature coefficient which can be positive or negative depending on the value of I_D relative to a given f.e.t. It has been shown[26] that a crossover point exists at which I_D is nearly independent of temperature, and MacHattie[27] has examined commercial devices to determine the precise value of I_D required. Moreover, if the current I_D is chosen so that the temperature coefficient is zero at the ambient temperature of the location in use, a variation of ± 5 deg C about this temperature results in less than 40 parts in 10^6 change in I_D. If this current is passed through a very stable resistor as is shown in Fig. 7, a reference voltage can be derived. Since I_D is typically about 0·5 mA, such a reference system will usually require to be 'buffered' by an amplifier having a suitably low input current much in the same way as in the case of a standard-cell reference (see Section 6.1).

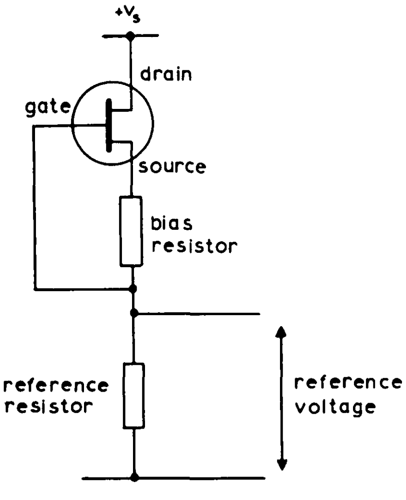

Fig. 7
Use of a field-effect transistor as a constant-current source

Tests on a typical f.e.t. reference of this kind, adjusted in the manner described above, equipped with a suitably stable reference resistor and fed from a suitably stabilised power supply, yielded a stability of 30 parts in 10^6 over 11 days.

A combination of the f.e.t. used in this way and a low-temperature-coefficient Zener diode is an extremely elegant and effective way to obtain a reference, and is much used.

5 Discussion of the relative merits of various types of voltage reference

The choice of reference device for a given application may often be governed by cost and convenience rather than by the technical specification. It has been shown in earlier sections that, for a reference having a stability between 0·1% and 0·01% per day, a wide choice exists. In small mains-powered equipment, where there is scope for employing suitable stabilising circuits, there seems little point in using anything other than a Zener reference diode. In larger, more complex equipment, where a number of independent power sources have to be stabilised, it may be necessary to use independent references to avoid interaction between the respective power supplies, in which case a set of reference batteries could be cheaper and simpler.

High-voltage references call for batteries or discharge tubes, unless the designer is prepared to generate the high voltage by circuit technique using a low-voltage Zener reference. Very-low-voltage references can be obtained by potential division from higher values, unless the equipment in question is required to operate from very-low-power supply voltages as is sometimes the case in portable instruments such as electronic multimeters.

For stabilities of a high order, e.g. 10 parts in 10^6 or better, Zener diodes of suitable quality are widely used. Where there is also a need for an absolute value of voltage, the saturated or unsaturated cadmium cell is an obvious choice, but it must be remembered that its stability cannot be relied upon under conditions of movement or vibration. Mercury cells do not have that disadvantage, but by comparison with the Weston cell have a rather short life.

There is some evidence that suitably selected diodes have a medium-term stability better than that of Weston cells. The US National Bureau of Standards have examined banks of Zener diodes and standard cells simultaneously in a closely controlled environment. They found, or at least were tempted to infer by means of cross correlations, that the cells exhibited very small medium-term fluctuations which were absent in the diodes. This seems a very good argument in favour of using Zener diodes for all portable and transportable instruments which are expected to give several years of service without recalibration.

Table 3 gives a summary of the main advantages and disadvantages of the principal types of reference.

Table 3
COMPARISON OF VOLTAGE REFERENCES

	Advantages	Disadvantages
Weston standard cell	absolute e.m.f. very low t.c. (5 μV/deg C) low noise long life	affected by vibration can supply very little current expensive
Mercury cell	robust very low internal resistance predictable e.m.f. small size	limited life moderately expensive
Leclanché cell	wide choice of e.m.f. readily available cheap	limited life high t.c. (400 μV/deg C)
Discharge tubes	provide high values of voltage robust	noisy subject to discontinuous changes t.c. not very low poor long term stability
Zener reference diode	cheap very low t.c. long life very robust small size	limited choice of voltage and current self-heating effects

6 Application of reference devices

6.1 Buffer amplifier

It has repeatedly been stressed that, in using voltage references, one should draw as little current as possible from the reference device. This is especially true of voltaic-cell references, particularly the Weston cell. The reference must therefore feed directly into an amplifier of high input impedance, or to be more exact, one in which the flow of direct current into the input terminal is very small. At the same time, the amplifier must have a stable gain, very often unity, and must have a stability of voltage-zero comparable to, or preferably much better than, the voltage stability of the reference. Finally, the effect of a drift in the value of input current must be assessed. This will give rise to a further voltage drift, namely, the product of the current change and the source resistance.

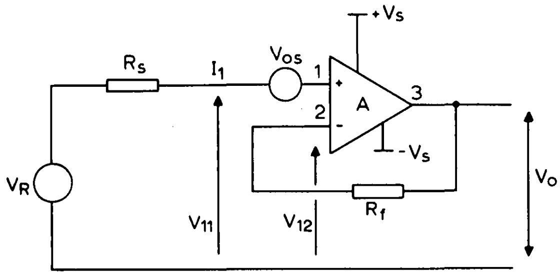

Fig. 8
Essential features of a unity-gain buffer amplifier

Because, in practice, the gain of the amplifier is stabilised by a large degree of feedback, a circuit model showing this feedback is worthy of discussion. Fig. 8 shows the essential features of a unity-gain system. The generator labelled V_{os} is part of the amplifier, and is called the input-voltage offset. This generator could equally well be regarded as being in input '2' since its polarity is arbitrary. The characteristics of the amplifier may be summarised by the equation

$$V_o = A(V_{11} - V_{12} \pm V_{os}) \qquad (5)$$

where A is positive and large (typically 10^4 or more). The output resistance is usually small enough to be neglected.

Taking the analysis a stage further, one can derive a value for V_o, the buffered reference voltage, taking into account the values of input current and the finite source resistance R_s, i.e.

$$V_o = (A/1 + A)(V_R \pm V_{os} + I_2R_f - I_1R_s) \qquad (6)$$

a relation which is derived from eqn. 5 by substituting appropriately for V_{11} and V_{12}. The amplifier would be ideal if $A = \infty$, $V_{os} = 0$ and $I_1 = I_2 = 0$. V_{os} can be reduced to an almost negligible value by means of a resistive network applied to the 'offset trim' terminals, which are to be found in most amplifiers of this class The extent to which this also reduces the temperature coefficient of the offset in amplifiers with bipolar input transistors has been examined by Hoffait and Thornton.[28] A practical limit seems to be 0·25 μV/deg C.

The effect of finite input current can best be understood by putting $I_1 = I$, $I_2 = I + I_{os}$ and $R_f = R_s + R_{os}$. I is then called the bias current, I_{os} the input offset current and R_{os} the offset resistance. Eqn. 6 then becomes

$$V_o = V_R \pm V_{os} + IR_{os} + I_{os}R_s \qquad (7)$$

Two further sources of drift are noticed: IR_{os} and $I_{os}R_s$. By careful circuit adjustment R_{os} can be made negligibly small leaving only the term which depends on I_{os}. For a very full discussion of all these factors see 'Operational amplifiers' by Graeme, Tobey and Huelsman.[29]

A wide choice of suitable amplifiers exists of which typical characteristics are listed in Table 4. The amplifiers are listed in decreasing order of input current.

Table 4
CHARACTERISTICS OF SOME LOW-DRIFT OPERATIONAL AMPLIFIERS

	Input bias current I	Input offset current I_{os}	Input offset voltage V_{os}	$\Delta V_{os}/\Delta T$	$\Delta I_{os}/\Delta T$
	nA	nA	mV	μV/deg C	nA/deg C
Monolithic	15	7	1	3	0·1
types	3	2	2	5	0·03
Chopper stabilised	20×10^{-3}	20×10^{-3}	30×10^{-3}	0·1	2×10^{-3}
F.E.T.	10×10^{-3}	5×10^{-3}	2	5	$0{\cdot}5 \times 10^{-3}$
input	1×10^{-3}	$0{\cdot}5 \times 10^{-3}$	1	1	$0{\cdot}5 \times 10^{-3}$

These amplifiers are arranged in descending order of input current. The characteristics or range of characteristics given for each of the three classes are thought to cover most applications at an economic price. They are not the best obtainable.

As with the selection of the reference device, cost tends to be a leading factor, and it may well be desirable to consider the joint cost of reference and amplifier before reaching a decision.

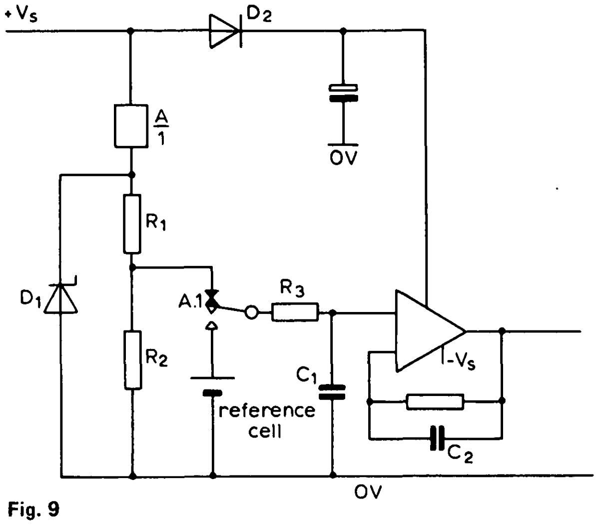

Fig. 9
Buffer amplifier with added protection circuits for use with voltaic-cell references

6.2 Protection of electrolytic cells

When reference cells are in use, a standby reference and change-over switch should be used, as is shown in Fig. 9. The cell is switched into circuit only when the power-supply line is activated. R_1, R_2 and D_1 provide an initial reference so that circuit equilibrium exists before the cell is called into use. R_3 and C_1 act as a noise filter; C_2 equalises the impedance presented to the feedback terminal. D_2 prevents the relay A from being held in the 'on' state, after a normal shutdown, by a flow of current derived from the reference cell acting through the amplifier.

6.3 Reference systems for low voltages

A Zener reference can be followed directly by a resistive voltage divider as in Fig. 10A, provided that the attenuated reference

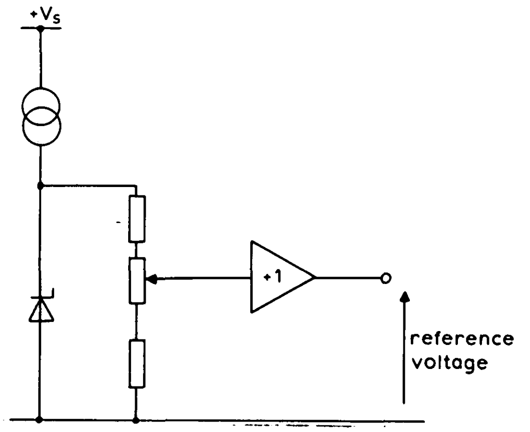

Fig. 10A
Use of a variable resistive attenuator in conjunction with a Zener reference

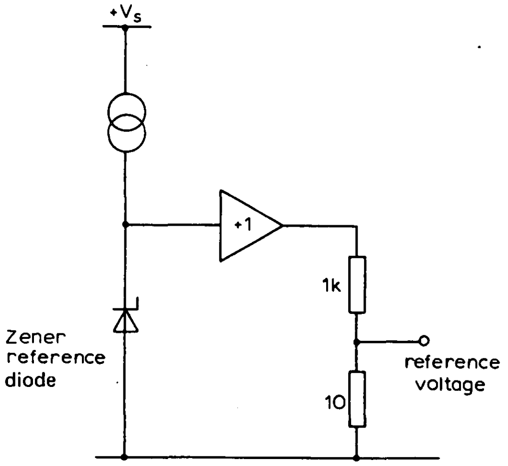

Fig. 10B
Use of a buffer amplifier to feed a low resistance reference attenuator

voltage is still much larger than the drift in the buffer amplifier. This is the normal method for obtaining an adjustable reference. If the required reference is less than 1 V, it will probably be preferable to place the attenuator after the amplifier, as in Fig. 10B or to incorporate both features by providing variable attenuation before the amplifier and a large fixed attenuation at the output.

Occasionally, the design engineer may be faced with the problem of having low-voltage supplies and a restricted power availability. Williams[30] has described an ingenious principle by means of which good regulation can be obtained using a 'ring-of-two' configuration. When this technique is applied to forward-biased *p–n* junctions rather than Zener diodes, low-value references are obtained and, at the same time, a measure of temperature compensation.[31] A complete reference system providing 100–200 mV, stable to 0·1%/deg C and requiring a power supply not greater than 1·6 V has also been described.[32] An alternative technique which has much the same performance has been described by the same author.[33] Yet another has similar performance but low power consumption.[34]

6.4 Reference systems for high voltages

Voltages higher than that of the reference device can be generated using feedback techniques. Extremely stable supplies have been devised at 10 kV using a nominal 1 V reference (standard cell).[6] Fig. 11 illustrates a regulating system, the performance of which depends mainly on the stability of the voltage divider R_1, R_2. The design of high-ratio voltage dividers requires great care, especially where high voltages are involved, and much has been written on the subject.[35] It is true that in a configuration such as that shown in Fig. 11, the divider ratio is reduced if a high-voltage reference is used, but, unless this is a battery, it poses further problems, namely the provision of a stable feeder supply for the reference. It is therefore unlikely that the designer will choose discharge tubes or high-voltage diodes as a primary reference. The use of a low-voltage Zener reference is further justified by the fact that a low-voltage stabilised auxilliary supply will be available for use with the low-drift amplifier which nowadays will be of solid-state construction.

6.5 Potentiometric applications

The provision of portable, variable-potential sources of high resolution and stability has received much attention by the manufacturing industry since the arrival of the highly stable Zener reference. Of particular interest are those types which have decade switching, enabling the user to select a voltage to perhaps 5 or 6 significant figures. A further development of this idea is the use of a factory made and calibrated, digital-to-analogue convertor as a component in a reference system. By this means, the designer can arrange that a reference voltage is subdivided with great accuracy by the application of a digital signal either in binary or binary-coded decimal form. This could prove to be a simple way of providing a voltage divider of very compact form, free from the problem of switch failure or contact resistance. Resolution to perhaps 1 part in 4000 (12 binary bits) is feasible in this way at moderate cost.

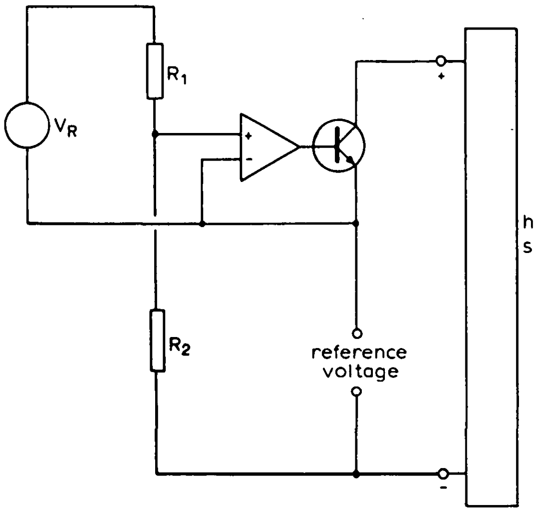

Fig. 11
System for generating a high-voltage reference

7 Conclusion

The provision of direct-voltage references of moderate stability (0·1% per year) in mains-powered portable equipment need present no problem. A Zener reference diode appears to be the best choice. Under laboratory conditions, Zener diodes can have a stability of 100 parts in 10^6 per year, and, with temperature control, short-term variations of no more than 1 part in 10^6 are reported, although the long-term stability is not likely to be better than 10–100 parts in 10^6. For the highest long-term stability, standard cells will be used, but they will require a stationary environment. Other types of cell or battery are likely to be used only in special cases where technical considerations outweigh the lack of convenience involved in regular replacement. The design of low-power, low-level references by circuit technique is well established. It usually involves a sacrifice of stability. In high-voltage applications the use of high-voltage references may be justified where a feedback system is not feasible or where a buffer amplifier is unnecessary. The convenience, cheapness and high performance of monolithic amplifiers, however, favours the choice of a low-voltage reference for most purposes.

8 References

1 National Bureau of Standards Monograph, 1962. 'A comparison of the medium and long term stability of solid-state reference diodes and standard cells'
2 BENSON F.A.:'Voltage stabilised supplies' (MacDonald, 1957) chap.8
3 GALLOP, J.C., and PETLEY, B W.: 'Recent NPL work on the a.c. Josephson Effect as a voltage standard', *IEEE Trans.*, 1972, **IM-21**, pp. 310–314
4 National Bureau of Standards Monograph, 1965. 'Standard cells, their construction, maintenance and characteristics'
5 RAAMOT J.: 'A secondary reference voltage source, stable to 1 ppm.' *Rev. Sci. Instrum.* 1970, **42**, pp. 440–441
6 BROOKSHIER, W.K.: 'Ultrastable voltage source to 10 kV using capacitive feedback', *ibid.*, 1966, **38**, pp.1245–52
7 Muirhead & Co. Ltd., Publication of extract of a paper by John M. Fluke and R.W. Hammond of Fluke Manufacturing Co. Ltd.
8 PATCHETT, G.N.: 'Automatic voltage regulators and stabilisers' (Pitman, 1954)
9 GREENWOOD, I.A., and HOLDAM, J.V., and MACRAE, D.: 'Electronic instruments' (McGraw-Hill 1948) Chaps. 15 and 16
10 RETSKY, M.W., and WALL, J.: 'One-ampere current supply stable to 1 ppm/hour' *Rev. Sci. Instrum.*, 1972, **43**, pp.384–385
11 TOWNSEND, J.S., and HURST, H.E. *Phil. Mag.*, 1904, **8**, pp. 738–752
12 TITTERTON, E. W.: 'Some characteristics of glow-discharge voltage-regulator tubes', *J. Sci. Instrum.*, 1949, **26**, pp. 33–36
13 BENSON, F.A., CAIN, W.E., and CLUCAS, B.D.: 'Variations in the characteristics of some glow-discharge voltage-regulator tubes' *ibid.*, 1949, **26**, pp. 399–401
14 BENSON, F.A.: 'The characteristics of some miniature, high-stability, glow-discharge, voltage-regulator tubes', *ibid.*, 1951, **28**, pp. 339–341
15 Mullard Ltd., Technical Handbook 2 (valves and tubes), 1971, Pt. 3, pp. D1–D9
16 KEMPLAY, J.R.: 'Measurement of noise pulses generated by SC1 corona discharge tubes' *J. Sci. Instrum.*, 1963, **40**, pp. 466–467
17 COHEN, E., and JENKINS, R.O.: 'The corona discharge and its application to voltage stabilisation', *Proc. IEE*, 1960, **107B**, pp. 285–294
18 BROWN, S.C.: 'Characteristics of the precorona discharge and its use as a reference potential in voltage stabilisers', *Rev. Sci. Instrum.*, 1946, **17**, pp. 543–549
19 MCAFEE, K.B., RYDER, E.J., SHOCKLEY, W., and SPARKS, M.: 'Observations of zener current in germanium *p–n* junctions', *Phys. Rev.*, 1951, **83**, pp. 650–651
20 MCKAY, K.G.: 'Avalanche breakdown in silicon', *ibid.*, 1954, **94**, pp. 877–pp. 877–884
21 ZENER, C.: 'Theory of electrical breakdown in solid dielectrics', *Proc. Roy. Soc.*, 1934, **145**, pp. 523–529
22 GARSIDE, A.E., and HARVEY, P.: 'The characteristics of silicon voltage-reference diodes', *Proc. IEE*, 1959, **106B**, pp. 982–990
23 WADDELL, J.M., and COLEMAN, D.R.: Zener diodes', *Wireless World*, 1960, **66**, pp. 17–21
24 CHYNOWETH, A.G., and MCKAY, K.G.: 'Internal field emission in silicon *p–n* junctions', *Phys. Rev.*, 1957, **106**, pp. 418–426
25 PALLET, J.E.: 'The transistor as a temperature-sensing device in temperature control systems', *Electron. Eng.*, 1961, **33**, pp. 360–363
26 SEVIN, L.J.: 'Field-effect transistors' (McGraw-Hill, 1965)
27 MACHATTIE, L E.: 'A highly stable current or voltage source', *J. Phys. E*, 1972, **5**, pp. 1076–1077
28 HOFFAIT, A.H., and THORNTON, R.D.: 'Limitations of transistor d.c. amplifiers', *Proc. IEEE*, 1964, **52**, pp. 179–184
29 GRAEME, J.G., TOBEY, G.E., and HUELSMAN, L.P. (Eds.), 'Operational amplifiers, design and applications' (McGraw-Hill, 1971)
30 WILLIAMS, P.: 'High-stability direct-voltage reference', *Electron. Lett.*, 1967, **3**, pp. 64–65
31 WILLIAMS, P.: 'Low-voltage ring-of-two reference', *Electron. Eng.*, 1967, **39**, pp. 676–679
32 WILLIAMS, P.: 'A d.c. regulator for low voltages'. *ibid.*, 1970, **42**, pp. 41–43
33 WILLIAMS, P.: 'A very low voltage reference', *ibid.*, 1968, **40**, pp. 348–349
34 ROSS, P.J.: 'A low power voltage regulator for field instrumentation', *J. Phys. E.*, 1973, **6**, pp. 969–970
35 VINCENT, C H.: 'Fixed attenuators consisting of a network of identical resistors', *J. Sci. Instrum.*, 1961, **38**, pp. 288–290