VOLTAGE REFERENCES

It is well documented in the annals of the science of electricity that most early experiments involved qualitative rather than quantitative information. Experimenters from the first century to the eighteenth century were largely concerned about how electrically charged objects would attract or repel each other, and whether this electricity was “resinous” or “vitreous”—that is, positive or negative. The only “measurement” concerned the polarity of the charge or voltage; the degree was generally not quantified except as “strong” or “weak.”

Nevertheless, as early as 1759 (1), Robert Symmer quantified the amount of charge generated by pulling a white silk stocking off a black worsted stocking. He would transfer the charge from one or more stockings into a Leyden jar (a capacitor constructed from a glass jar). He found that the charge from 2 silk stockings would shock him up to both elbows; but the charge from 4 silk stockings was sufficient to generate a shock all the way from his fingers to his elbows to his breast, and additionally to ignite a spoonful of brandy. It is interesting to note that 4 units of charge was required to ignite the brandy, but 3 units was not enough (2).

EARLY MEASURING INSTRUMENTS

Some of the earliest “meters” for detecting the quantity of electricity were galvanometers and electrometers. A *galvanometer* originally consisted of a compass needle that was deflected by a current passing nearby. The galvanometer’s sensitivity was soon increased by passing the current through a large number of turns of wire coiled around the needle. The strength of the current was thought to be proportional to the deflection of the needle, although the linearity of this relationship was not checked quantitatively.

An *electrometer* was typically made of two parallel strips of extremely thin metal. When a large voltage was applied between them, the metal strips would repel each other and be

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deflected. The mystique of this apparatus was enhanced by the use of gold for the materials; of course, gold was also useful because it is very malleable and can be hammered into extremely thin, flexible strips. Again, no specific statements about linearity were entertained, except for the notion of "weak" or "strong."

Still, it was recognized as early as the 1700s that the measurement of electricity by such meters could be quantified: if two voltages produced the same deflection, they were presumably equal. Likewise if two currents produced the same deflection in a galvanometer, they were equal. Eventually it was determined (Becquerel, 1840) that when two voltages were applied to an electrometer—or to a galvanometer—if the meter did not deflect, the amount of electricity was equal. This invention of the *null* mode (the differential voltmeter) is the essence of modern metrology. As it was obvious that the resolution of such apparatus depended on the sensitivity of the galvanometer, galvanometers were designed with exquisite delicacy. Improvements included adding a mirror, so that a deflection as small as $\frac{1}{100}$ deg (of angle) could be read as a deflection of several millimeters, for a light beam shining on a scale several meters away. Torsional balances were designed so that a long thin vertical wire could be sensitive to very small rotational forces (less than 0.1 mg · cm of torque). Advances in galvanometer resolution occurred quite rapidly in the 1800s, due to ingenious new structures. Still, as of 1894, only moving-magnet galvanometers were known; the invention of the moving-coil galvanometer lay 20 years in the future. Galvanometers continued to be used extensively up to the 1960s, and are sometimes used at present, due to their simplicity and good resolution. However, mechanical and electrical choppers with ac amplifiers have gradually supplanted them.

Other experiments were made to quantify electricity. In 1788 Alessandro Volta (3) applied voltage to the plates of a capacitor connected to an ordinary beam balance. As the voltage increased, the (tiny) amount of weight to balance the attractive force was measured. This provided some linkage and confirmation to electricity theories being developed at that time. It was a tedious method to measure voltage, but it *was* quantitative. Similarly, the amount of current through a galvanometer could also be related (linearly) to the amount of silver plated by that current from a solution onto an electrode. The mass of silver could be weighed precisely to provide a linear measure of the time integral of the current—again, a tedious, slow, messy measurement, but quantitative and linear. For example, a carefully conducted 1875 experiment by F. Kohlrausch determined that 10 A · s would plate out 11,363 ±2 μg of silver—a result within 2% of modern data (4).

The invention of the Wheatstone bridge by Samuel H. Christie (it was popularized by Sir Charles Wheatstone about 1843) (5) constituted a great advance in the measurement of resistance. The advantage arose because the balance of the bridge did not depend on the stability of an (unstable) voltage supply, but only on the ratio of the resistances in the arms of the bridge. This advance soon led to improved voltage measurement: now any two dc voltages could be compared by attenuating them with precisely known resistor dividers until an electrometer or galvanometer detected a null. The ratio of the voltages was easily calculated from the ratios of the resistive dividers. Now a stable reference—a good voltage cell, a *standard cell*—could be used to make accurate and useful voltage measurements. [Note that many modern reference books use the term "standard cell" for a block of integrated circuit (IC) functions that is stored in a computer and can be easily brought into a large IC.]

STANDARD CELLS

The earliest electrochemical cells, as discovered by Alessandro Volta in 1800 (6), were able to generate about a volt of electromotive force, using tin and silver or copper plates in a mild acid solution. These were not precision references, but were usable in many experiments, and led to improved cells with more power and better stability.

In the late 1800s, the best, most stable cell used as a standard was the Daniell cell (invented in 1836 by the English chemist John F. Daniell) (7). The cell consisted of a copper electrode in a copper sulfate solution and a zinc electrode in dilute sulfuric acid, the two solutions being separated by a porous partition (8). It put out a stable 1.101 V potential, but with high internal impedance. It was the precursor of modern ultrastable standard cells.

The saturated cadmium cell was developed by Edward Weston in the era 1893 to 1905, and was adopted as a standard in 1908. It is made in an H-shaped glass tube, which contains metallic mercury in the bottom of one leg, and a cadmium–mercury amalgam in the other leg (See Fig. 1.) In between the two electrodes are cadmium sulfate solution, mercurous sulfate paste, and cadmium sulfate crystals. This cell has an output of 1.018636 V at +20°C, and excellent stability, of the order of 1×10^{-6} per day, per week, or per month. Its primary disadvantage is its strong negative temperature coefficient (tempco), about −39.4 μV/°C at +20°C. This problem is overcome by assembling one or more of such cells in a stable

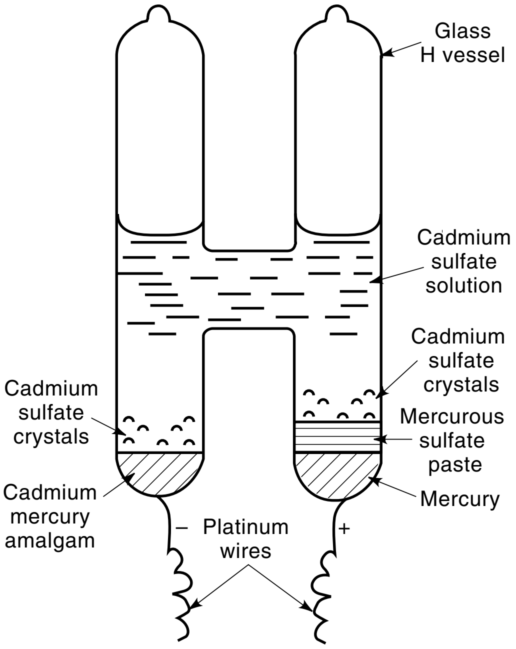

Figure 1. Arrangement of the elements of a saturated Weston cadmium cell.

temperature-controlled chamber maintained at +28° or +30°C. Another disadvantage is the degradation that occurs if even 1 nA dc is drawn from the cell for a long time, or 1 μA for a short time. This degradation can be avoided primarily by careful procedures to avoid drawing current from the cell, with the help of current buffers.

The other disadvantage lies in its instability if the cell is shaken, jiggled, or wobbled. Recovery to 20×10^{-6} is usually adequate in a few hours, but for full stability ($<2 \times 10^{-6}$) several days of rest must be allowed. This drawback is usually overcome by never moving the standard cells; unknown voltages or secondary standards are brought to the standards lab, where the standard cell is maintained at constant temperature, with no motion or vibration. The saturated standard cell is still in use today in standards laboratories, as it possesses superior stability, despite its drawbacks.

The unsaturated cadmium cell is constructed similarly, but without any surplus of cadmium sulfate crystals. It has the advantage of a lower tempco (around -10 μV/°C), but is not as stable as saturated cells.

GAS DISCHARGE TUBES

In the era 1920 to 1960, there was a need for stable references in portable equipment. Gas discharge tubes such as OA2, OB2, and 85A2 were used as references for precision regulators. If these tubes and the related amplifiers and resistors were powered up and warmed up and aged properly, good short-term voltage stability in the range 0.01% to 0.1% per 24 h could be observed (9). This was considered adequate for most portable precision equipment. However, the advice in Ref. 9 stated that a stack of two 42 V mercury batteries such as Mallory type RM415 would provide improved stability over the 85A2. The degree of improvement was not stated. Gas discharge tubes are still used in high-voltage equipment, but not much in new designs.

ZENER DIODES

Ever since the invention of the Zener diode in the 1950s, much hope has been engendered for using stable Zener diodes as stable references. Technically, diodes with breakdown below 5.4 V are true Zener diodes, which depend on a tunneling mechanism, whereas in diodes that break down above 5.4 V, the mechanism is avalanche breakdown. But the term "Zener diode" is applied to both types, unless there is some reason for distinguishing the mechanism.

Low-noise alloyed Zener diodes have existed since 1955. The Zener diode is made simply by doping a silicon *pn* junction so heavily that it breaks down at some useful voltage—typically in the range of 3 V to 200 V. Some Zener diodes have displayed good stability, and others have not. Most Zener diodes above 5.4 V have an inherent finite, positive, fairly constant tempco. To provide useful performance with low tempco, one or more forward diodes are then connected in series with the Zener. The forward diode chip is typically mounted right against the Zener chip, inside the conventional DO-35 glass diode package. The V_f of the forward diode (about -2 mV/°C) is used to cancel out the tempco of the Zener diode. The resulting reference voltage has, under favorable conditions, stability rivaling that of inexpensive standard cells. These references have the advantage of portability. They can operate (with degraded accuracy and stability) over temperature ranges where standard cells are impractical. Much effort has been put into evaluating Zener diode references. Not all of it has been completely successful. Early manufacturers of reference-type Zener diodes included Solitron, Hughes, PSI, and Motorola.

Alternatively, the Ref-Amp (10), invented by General Electric Corp., utilized an *npn* transistor with its emitter connected to the cathode of a low-noise alloy Zener diode chip, acting both as a temperature compensator and as a gain stage. The TO-5 package provided low stress, low hysteresis, and good stability.

The author has evaluated a 6.2 V Zener reference from a Minuteman I nose-cone guidance system. It was hoped that this reference from about 1960 might exhibit superior stability. Actually, when it was set up in a precision bias circuit and aged, it had a tendency to drift not much better than 10×10^{-6} or 20×10^{-6} per week, somewhat inferior to modern Zener references.

When early integrated circuit references were built, they were evaluated and compared with the best reference Zener diodes. Soon a serious problem was noted: the glass-packaged Zener diodes had a typical thermal hysteresis of 200×10^{-6} to 600×10^{-6} when cycled over a 100°C loop. This is manifested when a Zener diode is cycled cold and then hot and back to room temperature; its voltage will be different than when it is cycled hot and then cold and back to room temperature. Integrated circuits assembled in hermetic packages were observed to have typically 5 or 10 times better hysteresis, due to the smaller stress (and smaller change of stress) on the die. This is a characteristic of references that is not usually documented or even mentioned. These reference Zener diodes also showed some sensitivity to stress on their leads.

The best, most stable Zener references are often packaged with batteries and heaters in a portable temperature-controlled environment, just as saturated standard cells are. These instruments can be used as portable transfer standards. However they have not taken over the task from standard cells entirely, because their stability is not always as good. If the power is ever turned off, these Zener references sometimes exhibit a shift as large as 5 ppm—considerably bigger than that of standard cells—and not always reversible.

A study of low-tempco Zener references available in the 1972 era (11) showed at least 120 different JEDEC-registered part numbers, rated from $-25°$ to $+85°$C, plus 100 A-grade versions rated for the military temperature range of $-55°$ to $+125°$C. Many of them were for odd voltages (6.4 V, 8.4 V, 8.5 V, 9.3 V, 9.4 V, 11.7 V, 12.8 V, 19.2 V, 37.0 V, 37.2 V, etc.), at odd currents (choice of 0.5 mA, 1.0 mA, 2.0 mA, or 4.0 mA of bias current). However, as of this writing, almost all of these parts have been obsoleted or discontinued. A small number of popular, commercially viable reference-grade Zeners are still available, as listed in Table 1 (12).

INTEGRATED ZENERS

The LX5600 temperature-sensor IC, designed by Robert Dobkin at National Semiconductor Corp. (NSC) and introduced in 1973 (13), had a hidden agenda: in addition to the tempera-

Table 1. Commercially Available Zener References, 1998 (Ref. 12)

Types	Voltage[a] (V)	Current. (mA)	Tempcos (10^{-6} °C^{-1})	Manufacturers	Price ($/100)
1N821–829	6.2	7.5	100–5	Motorola, APD	$0.32–2.12
1N4565–4569	6.4	0.5	100–5	Motorola, APD	$0.71–6.52
1N4570–4574	6.4	1.0	100–5	Motorola, APD	$0.69–25.40
1N4575–4579	6.4	2.0	100–5	Motorola	$0.69–24.21

[a] Tolerance ±5%.

ture sensor, this chip had an experimental IC Zener reference. The Zener diode was connected in series with a transistor's base-to-emitter voltage V_{be}, and a buffer amplifier was provided. The reference's actual performance was fairly mediocre—the tempco was typically $+30 \times 10^{-6}$/°C, and the long-term stability was stated as 1000×10^{-6} per 1000 h at +85°C. Still, this temperature-sensor IC went into production as a test bed, and the engineers were able to evaluate a large number of the diodes. Best of all, the construction of a temperature sensor on the same chip as the Zener reference made it easy to operate the temperature sensor as a temperature controller, and to make a little oven around the Zener, holding it at a very stable temperature (such as +88°C). It was easy to evaluate a large number of these references, operating at a constant temperature.

This study soon led to the LM129 and LM199 IC references (14).

The LM129 was an improved, simplified, upgraded version of the LX5600's reference, with a series resistance better than 1 Ω, and a tempco typically in the range 10×10^{-6}/°C to 60×10^{-6}/°C. These ICs could be tested (and graded in production test) for 50, 20, or 10×10^{-6}/°C.

The LM199 was a new design. It used an integrated temperature controller on the die, to hold the die temperature at +88°C. It was housed in a four-lead TO-46 package (similar to a low-profile TO-18). A small plastic thermal shield over the package was used to minimize the power needed to hold the whole IC at that temperature. Under these conditions, the LM199's reference could show a usable tempco better than 2×10^{-6}/°C, 1×10^{-6}/°C, or even $\frac{1}{2} \times 10^{-6}$/°C, selected and tested, over a temperature range from −55° to +85°C. Of course, this temperature-controlled IC did require a significant amount of power for the heater (typically 260 mW at 25°C, and even more at low ambient temperatures) to hold that +88°C temperature. But this was an acceptable requirement in many systems.

The temperature sensitivity of any temperature-stabilized circuit depends at least as much on the layout of the heat-sensitive components, and on the gradients caused by the heater, as on the tempco of the circuit. Thus the LM199's good tempco is related to good die layout.

Further disadvantages of the LM199 were its tolerance (±2%) and the fact that its nominal voltage (6.95 V) was not as convenient as 5.000 V or 10.000 V or even 6.20 V. And unless a charge pump was added, the LM129 or LM199 could not run on 5 V—it needed at least 8 V, at 1 mA for the reference and at 50 mA for the heater. These disadvantages led to efforts to develop improved circuits that avoided some of these drawbacks.

The other significant advantage of the LM129 (and LM199) resided in its buried (subsurface) Zener diode. In most Zener references the breakdown occurred at the surface, where the concentration of impurities (doping) was maximum. Thus, surface contamination (even with high-quality planar processing) and electron charging of the oxide caused some degradation of noise and of long-term stability. The invention by Carl Nelson and Robert Dobkin of shallow diffusion layers with decreased concentrations at the surface caused the Zener breakdown to occur about a micron below the surface of the IC, where it is immune to surface conditions. This allowed superior consistency of low noise and better long-term stability.

Extensive testing of large numbers of LM199s showed that a large fraction of the units exhibited reference stability consistently better than 10×10^{-6} or 5×10^{-6} per 1000 h, when sampled once a week. (However, some units were consistently worse than 20×10^{-6} per 1000 h.) The units that tested better than 20×10^{-6} per 1000 h were designated LM199AH-20 and LM299AH-20, and were used in many precision systems as stable references. Also, they were popular in high-resolution DVMs. The LM199 is still the only successful temperature-stabilized IC in the industry.

Several good selected LM299AH references were evaluated by the National Bureau of Standards (NBS, now the NIST). They found that the long-term drift tendency was about -1×10^{-6} per 1000 h, a fairly consistent drift, presumably related to operation at the die temperature of +88°C.

Other researchers found that if one group of LM299AHs were kept around room temperature, with their heaters off, and another group allowed to run at their normal temperature of +88°C, the long-term drift trend of the units at room temperature was considerably lower than that of the warm units. The room-temperature units could be heated up to their normal +88°C on a specified schedule, perhaps one day per 3 months, and used to calibrate out the long-term drifts of the units kept at +88°C.

The use of buried Zener diodes has spread to other ICs. The LT1021 (15), designed by Carl Nelson at Linear Technology Corp. (LTC), used a buried Zener diode with temperature-compensating circuits and after-assembly trims to achieve 2×10^{-6}/°C, without any heater. The LM169 (16) was engineered by Robert Pease at NSC to do likewise.

The LTZ1000 is a buried Zener designed by Robert Dobkin of LTC for laboratory standard use. All resistors are off chip, so that high-stability resistors can be utilized. Its on-chip heater can be activated for thermal stabilization. The die attach uses bubble material for high thermal impedance, as high as 400°C/W. Long-term stability approaching 1×10^{-6} is claimed (17).

The Analog Devices AD534 Multiplier IC was designed by Barrie Gilbert (18) using a buried Zener diode. The Analog Devices AD561 was a complete digital-to-analog converter (DAC) IC designed by Peter Holloway and Paul Brokaw, utilizing a buried Zener diode and tempco trim circuits to achieve a gain tempco better than 10×10^{-6}/°C (19).

Further research and development into circuits with buried Zener diodes has waned, due to the improvements in bandgap references and to the concentration of research on low-voltage circuits and on CMOS technology, which precludes the use of buried Zener diodes.

The design of a good reference on a large CMOS chip is not trivial. In many cases, a mediocre on-chip bandgap reference is adequate for a system on a chip. If a superior reference is needed, an external (off-chip) reference is often added. This can often provide cost, performance, and yield advantages.

BANDGAP REFERENCES

The concept of the bandgap reference was first published by David Hilbiber of Fairchild Semiconductor in 1964 (20). If a suitable circuit is used to add voltages with both positive and negative temperature coefficients, until the output voltage is approximately the same as the bandgap voltage of the material used (1.205 V for silicon, 0.803 V for germanium) a stable, low-tempco reference can be achieved.

The invention of the LM113 bandgap reference IC (21) by Robert J. Widlar in 1971 was rather like the birth of a baby—just a beginning. While this small IC was useful for instrument makers who needed a reference that would run on low voltages (such as 4.5 V or 3 V or even 1.5 V), it definitely did not have superior performance. The standard LM113 had an output voltage of 1.220 V with a tolerance of ±5%, a fairly broad spread of temperature coefficients, and mediocre long-term stability. Still, the principle and the feasibility of the bandgap reference had been proved, and the development of new bandgap reference circuits with needed improvements soon commenced. These efforts have continued for well over 25 years without much diminishment.

The bandgap reference was first used in the NSC LM113 reference circuit (1971) and the LM109 Voltage Regulator (1969) (22). The bandgap circuit employs transistors operating at different current densities, such as 10 μA flowing through one transistor with one emitter, and the same amount of current flowing through another transistor 10 times as big. This generates a voltage (ΔV_{be}) of perhaps 60 mV, which is a *voltage proportional to absolute temperature* (VPTAT). This voltage is amplified and added to a voltage proportional to the transistor's base–emitter voltage V_{be}, which *decreases* fairly linearly with temperature. The addition is scaled so that the total voltage is about 1.24 V dc. When the reference voltage is set or trimmed to this voltage, a low tempco is obtained.

The principle of the bandgap reference relies on a good understanding of the V_{be} of transistors. Widlar's paper (23) on this subject clarified the mathematics and physics of V_{be} and corrected various misconceptions.

We refer to the example of the LM113. In Fig. 2, the LM113 schematic diagram shows a basic bandgap circuit. When V_+ is around 1.22 V dc, Q_1 runs at a high current density, about 230 nA/μm^2. Q_2 is operated at a low density, about 15 nA/μm^2, and so its V_{be} is much smaller, by about 70 mV. Now, let's *assume* that the circuit is at balance and the output is near 1.22 V. Then the 70 mV across R_5 is magnified by the ratio of R_4 to R_5, about 8.5 : 1, up to a level of 600 mV. This voltage is added to the V_{be} of Q_4 (about 620 mV at room temperature) to make a total of 1.22 V, as required. Q_4 then amplifies the error signal through Q7 and Q9, which provide enough gain to hold the V_+ bus at 1.22 V. The beauty of the bandgap reference is the summation of the V_{be} term, which decreases at the rate of about −2 mV/°C, and the ΔV_{be} term, which grows at about +2 mV/°C, to achieve an overall tempco that is substantially zero. All bandgap references employ this summation of a growing and a shrinking voltage to make a stable low-tempco voltage. Further, it has been shown (23) that when a circuit has been trimmed to the correct voltage, the correct tempco will follow, despite process variations in parameters such as V_{be}, β, sheet resistivity, etc. Consequently, bandgap circuits are often trimmed to their ideal voltage so as to provide a low tempco.

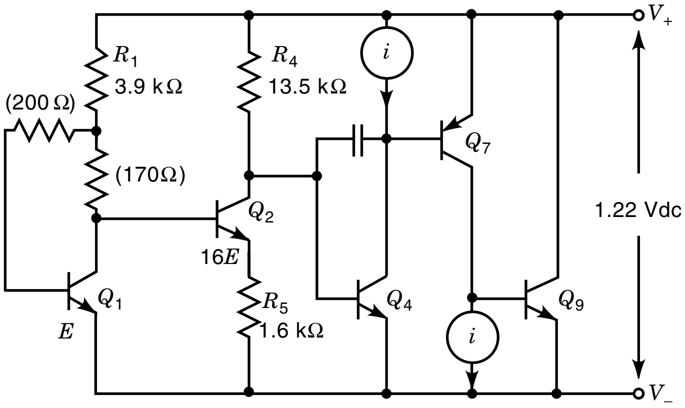

Figure 2. Schematic diagram, LM113 (simplified).

Since the LM109 and LM113 were introduced, many other circuits and configurations have been invented for bandgap references. The *Brokaw cell* is often used for output voltages larger than 1.25 V, as its V_{out} can be scaled by the ratio of two built-in resistors, R_3 and R_4. This unit, the AD580, was introduced in 1974 (24) (Fig. 3).

A similar circuit is used in the LM117 (25), whose output can be set by two external resistors R_7 and R_8 to any voltage in the range 1.25 V to 37 V (Fig. 4).

The above information was excerpted from an invited paper at the IEEE Bipolar Circuits and Technology Meeting, 1990 (26). The paper includes much information on how to

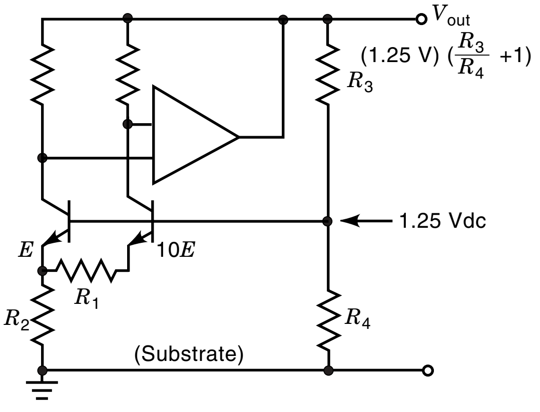

Figure 3. Schematic diagram, AD580 (simplified).

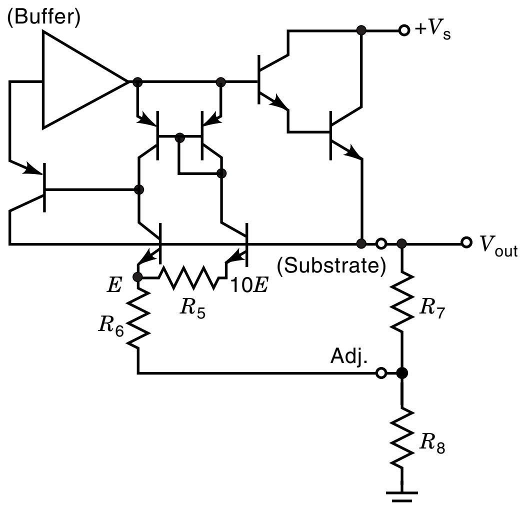

Figure 4. Schematic diagram, LM117 (simplified).

engineer a bandgap reference badly, and a little information on how to do it right. The paper is accessible on the World Wide Web at: http://www.national.com/rap/Application/0,1127,24,00.html

The bandgap reference was soon introduced into many kinds of voltage regulator ICs, instead of the old Zener references. Many of these ICs showed improved performance in one aspect or another. But most of these regulators had low accuracy, and will not be considered here. Our study here will concentrate on precision references with much better than 1% accuracy and tempcos much better than 50×10^{-6}/°C.

Paul Brokaw at Analog Devices, Wilmington, MA, designed a curvature-correction circuit that canceled out the normal quadratic dependence of the bandgap's output on temperature. The temperature drift over a 70°C span was reduced below 5×10^{-6}/°C. These were introduced in the AD581, about 1976. The related US patent (27) showed how to use different types of IC resistors, with different tempcos, to correct for the curvature.

Robert Widlar designed the NSC LM10 IC bandgap reference (28). This circuit had a reference output of 0.200 V, which was easily scalable by external resistors up to 39 V. The basic reference was able to run on a 1.1 V power supply. It included curvature correction (29).

At NSC, Carl Nelson designed a quadratic curvature correction circuit suitable for curvature correction of bandgap references and temperature sensors, as described in a US patent (30). This was first introduced on the LM35 temperature sensor (31). While at LTC, Nelson later designed an improved logarithmic curvature-correction scheme (32). This circuit was introduced in the LT1019 (33).

Derek Bowers at Analog Devices designed a modified type of reference IC circuit that does not rely on the ΔV_{be} of transistors operated at different current densities. It depends on the offset of the threshold voltages of two junction field-effect transistors (JFETs) made with different implant doses. This IC was introduced in 1997 as the ADR291 (34). It has a typical long-term stability of only 100×10^{-6} per 1000 h at +150°C. The ADR291 as introduced does not have sufficiently low tempco or gain error to permit such excellent long-term stability to be fully appreciated. But since the feasibility of this principle has been demonstrated, it is foreseeable that ICs with fully optimized performance will be available soon.

Most of these IC references are not usable directly as standards. However, the ones with the best specifications have adequate stability and are suitable for portable standards in small systems. They may need auxiliary circuits for trims, calibration, tempco correction, and so on—just as a Weston standard cell needs an oven to be useful.

HYBRID IC REFERENCES

For many years, makers of hybrid ICs were able to include chips of different technologies, wired together on a small ceramic substrate. For example, the old NSC LH0075 (introduced in 1975 but now out of production) included a quad opamp chip, an LM329 IC reference, and several laser-trimmed resistors. The trimming provided advantages of improved output accuracy, and a convenient 10.00 V output voltage level rather than the 6.95 V of the reference itself.

Likewise, modern hybrid IC references such as Thaler Corp.'s Models VRE100/101/102 use chips of different technologies (Zener diodes, precision trimmable resistors, operational amplifiers, and thermistors) to provide the same kinds of advantages, such as output voltages trimmed to ±0.005%, and temperature coefficients better than $\pm 0.6 \times 10^{-6}$/°C or $\pm 0.3 \times 10^{-6}$/°C. Output voltages such as +10 V or −10 V dc (or both) to as low as +1.5 V or −1.5 V are available (35).

FEATURES OF BANDGAP AND INTEGRATED-CIRCUIT REFERENCES

As mentioned above, many kinds of ingenious internal architectures have been used for bandgap references. The actual topology of the bandgap elements has been arranged in many ways—ways that may (or may not) be transparent to the user. However, there are also *features* that are useful to some users and of no value to other users. A list of typical features is provided here, along with a brief list of typical ICs that include those features. This list of ICs is by no means intended to be exhaustive, but merely indicative of what features one might look for.

- *Low Power.* Many users like the advantages of low power, but often a low-power bandgap reference is noisy, because transistors operated at small currents tend to have voltage noise inversely proportional to the square root of the emitter current. LM185-1.2 (10 μA), ADR291 (15 μA).
- *Low Noise.* A bandgap reference operated at higher current tends to be less noisy. LM336, ADR291.
- *Shutdown.* Sometimes it is important to turn the device off for minimum system power drain.
- *Startup.* Not all references start up very quickly.
- *Shunt-Mode Operation.* In some applications, a shunt-mode reference (which looks like a Zener) is easier to apply. LM4040, LM336, LT1009, AD1580.
- *Series-Mode Operation.* For applications where the load current may vary, series mode can be advantageous. AD581, LT1019, many others.
- *Output Can Sink or Source Current.* Sometimes it is convenient if the output can drive load currents in both di-

rections. If you need this, be cautious, as load regulation when sinking is usually inferior to when sourcing. MAX6341, AD581, LT1019, many others.

- *Output Is Trimmable—in a Narrow Range.* Beware that if you use this feature to adjust V_{out} a significant amount, the tempco may be degraded.
- *Output Is Adjustable—over a Wide Range.* This is sometimes a nice feature, but the accuracy, stability, and tempco of external resistors must be considered. LM385 (adjustable), LM4041-ADJ.
- *Filter Pin.* As band-gap references are fairly noisy (sometimes comparable to 1 LSB of a 10- or 12-bit system) a provision for an external noise filter capacitor is sometimes very useful. LM369, AD587.
- *Temperature Sensor.* Some units provide a temperature sensor output at −2.2 mV/°C. REF01, LT1019, many others.
- *Heater.* Some units provide a resistor on-chip that can be used to heat the unit to a constant warm temperature. LT1019.
- *Low-Dropout Regulator.* Many modern references need a supply voltage only 0.1 V or 0.2 V larger than V_{out}: a popular feature. See also below.
- *Requirement for Capacitive Load.* Most low-dropout references require a capacitive load on their output to prevent oscillations: an unpopular feature, as sometimes the capacitor is bigger or more expensive than the IC.
- *Tolerance of C_{load}.* Some references will tolerate any capacitive load, and may not require any load capacitor at all. LM385, LT1009.
- *Low Tempco.* A very desirable feature.
- *After-Assembly Trim.* This is a procedure for optimizing the low tempco of a reference. However, it uses pins for connection to in-circuit trims such as fuses or Zener zaps—so that these pins cannot be used for other features. LT1019, LM169.
- *Small Packages.* Many small systems require surface-mount devices. Packages such as SO-8 or SOT-23 are popular. However, tiny plastic packages tend to cause stresses which may degrade long-term stability.
- *Long-Term Stability.* A very desirable feature, but not trivial to find, and not easy or inexpensive to test for. In fact, stability is just about the most expensive specification that one can buy on a reference.
- *Compromises.* No reference can provide every advantage, so priorities and tradeoffs must be engineered.
- *Price.* Any combination of excellent features and/or specifications is likely to command a high price. This leads to compromises; see above.

THE JOSEPHSON JUNCTION

As early as 1972, the advent of the ac Josephson junction promised to provide improved accuracy in its representation of the volt standard. When microwave energy at a precisely known frequency is injected into a stacked assembly of Josephson junctions, held at 4 K by liquid helium, it is possible to generate a voltage that is accurate and stable to better than 0.1 μV/V, both theoretically and in practice (36).

Preliminary research confirmed that even the best Weston saturated standard cells had unexplained drifts and noises, of the order of 1×10^{-6}, which the Josephson junctions did not. As the Josephson junction equipment became more reliable and easier to operate, it became obvious that they would soon make possible a new, more stable standard. After a considerable amount of engineering and development, a new representation of the volt was established. The Josephson constant $K_{J\text{-}90}$, adopted on January 1, 1990, was defined as 483,597.900 GHz/V, exactly.

The ac Josephson junction equipment for establishing ultraprecise voltage references has typically a precisely known 72 GHz input frequency, and an output of 2.0678336 μV/GHz. The output of each junction is about 149 μV. To provide an output at a convenient level, an array of 2000 Josephson junctions is integrated, stacked in series, and enclosed in the cryogenic (4 K) microwave-stimulated chamber, thus providing an output of perhaps 298 mV. This voltage is compared with the 1.018 V level using conventional potentiometric techniques, to calibrate the standard cells that act as secondary transfer references. Equipment to implement this stable reference tends to cost in the vicinity of $100,000, plus considerable labor and operational costs.

Thus on January 1, 1990, the magnitude of the US volt (as well the voltage standards in most other countries) was changed. The new 1990 US volt was established as +9.264 μV/V larger than the previous (1972) US standard. Since 1990, the international standard volt has still been *defined* as 1 W/1 A, but the standard representation of the volt is the output of the Josephson junction apparatus.

THE AMPERE

In theory, the volt is not an absolute standard. The volt has long been defined as the potential such that 1 V × 1 A = 1 W. In turn the ampere is defined as an absolute standard, such that 1 A flowing through a pair of very long wires (of negligible diameter), separated by 1 m, will cause a force of 2×10^{-7} N per meter of length. In practice, the volt is a much more useful and usable standard. The ampere standard is not very portable. In fact, when a 1 A standard is required, it is normally constructed by establishing 1 V and 1 Ω, causing 1 A to flow.

THE OHM

In theory, the ohm is not an absolute standard, but the ratio 1 V/1 A, with the volt and ampere defined as above. As of 1990, the representation of the ohm was redefined using the quantum Hall effect (QHE), discovered by Klaus von Klitzing (37):

> The QHE is characteristic of certain high-mobility semiconductor devices of standard Hall-bar geometry, placed in a large applied magnetic field and cooled to a temperature near one kelvin. For a fixed current I through a QHE device there are regions in the curve of Hall voltage vs. gate voltage, or of Hall voltage vs magnetic field depending on the device, where the Hall voltage U_H remains constant as the gate voltage or magnetic field is varied. These regions of constant Hall voltage are termed Hall plateaus. Under the proper experimental conditions, the quantized Hall re-

> sistance of the ith plateau $R_H(I)$, defined as the quotient of the ith plateau to the current I, is given by
>
> $$R_H(i) = U_H(i)/I = R_K/i$$
>
> where i is an integer and R_K is now termed the von Klitzing constant after the discoverer of the QHE . . ..
>
> Numerically, R_K is about 25,813 ohms. The value agreed upon as an international constant was $R_{K\text{-}90}$ = 25,812.807 ohms.

This was a considerable improvement, as the best older standard resistors were shown to be drifting at about $-0.1\ \mu\Omega/\Omega$ per year. With the quantum standard, such drifts are banished.

PRECISION MEASUREMENTS

In classical metrology, one uses a precision (six-digit, seven-digit, or eight-digit) voltage divider, known as a *potentiometer.* This has very little in common with the variable resistor often called a "potentiometer" or "pot"—but it does act as a voltage divider. When such a precision potentiometer is used with a null meter, any voltage can be compared with a standard or reference voltage. The unknown voltage is thus well determined, according to the ratio of the potentiometer and the standard voltage (allowing for its uncertainty.) However, most precision potentiometers are not guaranteed to maintain their linearity to 1 LSD (Least Significant Digit) for long-term accuracy, after their resistive dividers are trimmed and calibrated. A good potentiometer may hold better than 1×10^{-6} linearity per year, but it is not guaranteed that switching from 0.499999 to 0.500000 will not cause a *decrease* of its output. Further, an inexperienced user may find it very time-consuming to use such a divider. When taking a large number of data, long-term system drift may cause errors that could be avoided by taking data more quickly.

The author's recommendation is to use a good six-digit or seven-digit multislope integrating digital voltmeter (DVM), with 1×10^{-6} inherent differential linearity and excellent overall (end-to-end) linearity. The author has had excellent experience with HP 3456, 3457, 3468, and other similar integrating voltmeters. Differential nonlinearity has never been observed to exceed 1×10^{-6} of full scale, on 10 V scales. Noise, offsets, and gain errors are usually acceptably small. For best absolute accuracy, the DVM's full-scale factor should be compared with other stable references. Note that not all six-digit or seven-digit DVMs have this inherent linearity.

CONCLUSION

Since most advances in references are designed by IC manufacturers on a commercial basis, to be aware of good new products, one must inquire of the IC manufacturers, to see what is available. A list of IC makers is provided here, as well as a list of companies making precision references and measuring equipment.

MANUFACTURERS

High-Precision Instruments for Voltage Standards

- Datron Systems Division, 200 West Los Angeles Ave., Simi Valley, CA 93065-1650. Phone: 805-584-1717. Fax: 805-526-0885.
- The Eppley Laboratory, Inc., 12 Sheffield Avenue, Newport, RI 02840. Phone: 401-847-1020. Fax: 401-847-1031.
- Fluke Corporation, MS 250, P.O. Box 9090, Everett, WA 98206-9090. Phone: 800-44F-LUKE or 425-347-6100. Fax: 425-356-5116.
- Hewlett Packard Co., Electronic Measurement Systems, 815 14th Street SW, P.O. Box 301, Loveland, CO 80538. Phone: 970-679-5000. Fax: 970-679-5954.
- Julie Research Laboratories, Inc., 508 West 26th Street, New York, NY 10001. Phone: 212-633-6625. Fax: 212-691-3320.
- Keithley Instruments, 28775 Aurora Road, Cleveland, OH 44139. Phone: 800-552-1115 or 440-248-0400. Fax: 440-248-6168.

Voltage Reference Integrated Circuits

- Analog Devices Inc., 1 Technology Way, P.O. Box 9106, Norwood, MA 02062-9106. Phone: 781-329-4700. Fax: 781-326-8703.
- Burr Brown Corp., International Airport Industrial Park, 6730 South Tucson Boulevard, P.O. Box 11400, Tucson, AZ 85734. Phone: 800-548-6132 or 520-746-1111. Fax: 520-889-1510.
- LTC (Linear Technology Corp.), 1630 McCarthy Boulevard, Milpitas, CA 95035-7417. Phone: 408-432-1900. Fax: 408-434-0507.
- Maxim Integrated Products, 120 San Gabriel Drive, Sunnyvale, CA 94086-9892. Phone: 408-737-7600. Fax: 408-737-7194.
- NSC (National Semiconductor Corp.), MS D2565, 2900 Semiconductor Drive, Santa Clara, CA 95051. Phone: 408-721-8165 or 800-272-9959. Fax: 800-737-7018.
- Thaler Corp., 2015 North Forbes #109, Tucson, AZ 85745. Phone: 800-827-6006 or 520-882-4000. Fax: 520-770-9222.

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ROBERT A. PEASE
National Semiconductor Corp.

VOLTAGE SAG. See POWER QUALITY.

VOLTAGE STABILITY. See POWER SYSTEM STABILITY.