# How to Choose a Voltage Reference

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## Why Voltage References?

It is an analog world. All electronic devices must in some way interact with the "real" world, whether they are in an automobile, microwave oven or cell phone. To do that, electronics must be able to map real world measurements (speed, pressure, length, temperature) to a measurable quantity in the electronics world (voltage). Of course, to measure voltage, you need a standard to measure against. That standard is a voltage reference. The question for any system designer is not whether he needs a voltage reference, but rather, which one?

A voltage reference is simply that—a circuit or circuit element that provides a known potential for as long as the circuit requires it. This may be minutes, hours or years. If a product requires information about the world, such as battery voltage or current, power consumption, signal size or characteristics, or fault identification, then the signal in question must be compared to a standard. Each comparator, ADC, DAC, or detection circuit must have a voltage reference in order to do its job (Figure 1). By comparing the signal of interest to a known value, any signal may be quantified accurately.

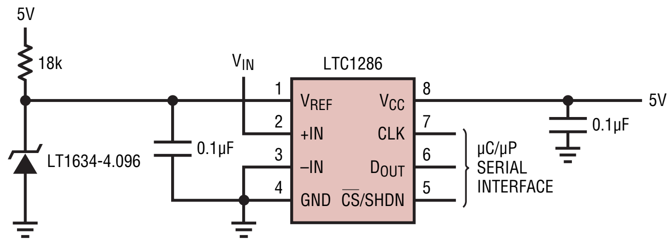


**Figure 1. Typical use of a voltage reference for an ADC**

## Reference Specifications

Voltage references come in many forms and offer different features, but in the end, accuracy and stability are a voltage reference's most important features, as the main purpose of the reference is to provide a *known* output voltage. Variation from this known value is an error. Voltage reference specifications usually predict the uncertainty of the reference under

**Table 1. Specifications for high performance voltage references**

| | Temperature Coefficient | Initial Accuracy | $I_S$ | Architecture | $V_{OUT}$ | Voltage Noise* | Long-Term Drift | Package |
|---|---|---|---|---|---|---|---|---|
| **LT1031** | 5ppm/°C | 0.05% | 1.2mA | Buried Zener | 10V | 0.6ppm | 15ppm/kHr | H |
| **LT1019** | 5ppm/°C | 0.05% | 650µA | Bandgap | 2.5V, 4.5V, 5V, 10V | 2.5ppm | | SO-8, PDIP |
| **LT1027** | 5ppm/°C | 0.05% | 2.2mA | Buried Zener | 5V | 0.6ppm | 20ppm/ month | SO-8, PDIP |
| **LT1021** | 5ppm/°C | 0.05% | 800µA | Buried Zener | 5V, 7V, 10V | 0.6ppm | 15ppm/kHr | SO-8, PDIP, H |
| **LTC6652** | 5ppm/°C | 0.05% | 350µA | Bandgap | 1.25V, 2.048V, 2.5V, 3V, 3.3V, 4.096V, 5V | 2.1ppm | $60ppm/\sqrt{kHr}$ | MSOP |
| **LT1236** | 5ppm/°C | 0.05% | 800µA | Buried Zener | 5V, 10V | 0.6ppm | 20ppm/kHr | SO-8, PDIP |
| **LT1461** | 3ppm/°C | 0.04% | 35µA | Bandgap | 2.5V, 3V, 3.3V, 4.096V, 5V | 8ppm | $60ppm/\sqrt{kHr}$ | SO-8 |
| **LT1009** | 15ppm/°C | 0.2% | 1.2mA | Bandgap | 2.5V | | 20ppm/kHr | MSOP-8, SO-8, Z |
| **LT1389** | 20ppm/°C | 0.05% | 700nA | Bandgap | 1.25V, 2.5V, 4.096V, 5V | 20ppm | | SO-8 |
| **LT1634** | 10ppm/°C | 0.05% | 7µA | Bandgap | 1.25V, 2.5V, 4.096V, 5V | 6ppm | | SO-8, MSOP-8, Z |
| **LT1029** | 20ppm/°C | 0.20% | 700µA | Bandgap | 5V | | 20ppm/kHr | Z |
| **LM399** | 1ppm/°C | 2% | 15mA | Buried Zener | 7V | 1ppm | $8ppm/\sqrt{kHr}$ | H |
| **LTZ1000** | 0.05ppm/°C | 4% | | Buried Zener | 7.2V | 0.17ppm | $2µV/\sqrt{kHr}$ | H |

*0.1Hz–10Hz, Peak-to-Peak

certain conditions using the following definitions.

**Initial Accuracy**

The variance of output voltage as measured at a given temperature, usually 25°C. While the initial output voltage may vary from unit to unit, if it is constant for a given unit, then it can be easily calibrated.

**Temperature Drift**

This specification is the most widely used to evaluate voltage reference performance, as it shows the change in output voltage over temperature. Temperature drift is caused by imperfections and nonlinearities in the circuit elements, and is often nonlinear as a result.

For many parts, the temperature drift, TC, specified in ppm/°C, is the dominant error source. For parts with consistent drift, calibration is possible. A common misconception regarding temperature drift is that it is linear. This leads to assumptions such as "the part will drift a lesser amount over a smaller temperature range." Often the opposite is true. TC is generally specified with a "box method" in order to give an understanding of the likely error over the entire operating temperature range. It is a calculated value based only on minimum and maximum values of voltage, and does not take into account the temperatures at which these extrema occur.

For voltage references that are very linear over the specified temperature range, or for those that are not carefully tuned, the worst-case error can be assumed to be proportional to the temperature range. This is because the maximum and minimum output voltages are very likely to be found at the maximum and minimum operating temperatures. However, for very carefully tuned references, often identified by their very low temperature drift, the nonlinear nature of the reference may dominate.

For example, a reference specified as 100ppm/°C tends to appear quite linear over any temperature range, as the drift due to component mismatches completely obscures the

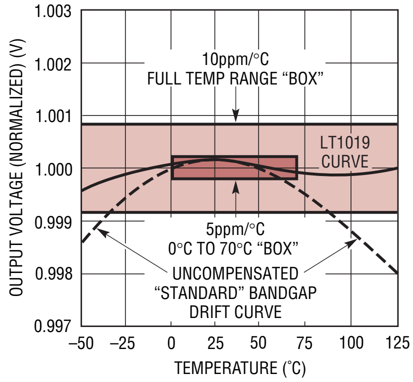


**Figure 2. Voltage reference temperature characteristics**

inherent nonlinearity. In contrast, the temperature drift of a reference specified as 5ppm/°C will be dominated by the nonlinearities.

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This can be easily seen in the output voltage vs temperature characteristic of Figure 2. Note that there are two possible temperature characteristics represented. An uncompensated bandgap appears as a parabola, with minima at the temperature extrema and maximum in the middle. A temperature compensated bandgap, such as the LT1019, shown here, appears as an "S" shaped curve, with greatest slope near the center of the temperature range. In the latter case, nonlinearity is exacerbated so that the aggregate uncertainty over temperature is reduced.

The best use of the temperature drift specification is to calculate maximum total error over the specified temperature range. It is generally inadvisable to calculate errors over unspecified temperature ranges unless the temperature drift characteristics are well understood.

**Long Term Stability**

This is a measure of the tendency of a reference voltage to change over time, independent of other variables. Initial shifts are largely caused by changes in mechanical stress, usually from the difference in expansion rates of the lead frame, die and mold compound. This stress effect tends to have a large initial shift that reduces quickly with time. Initial drift also includes changes in electrical characteristics of the circuit elements, including settling of device characteristics at the atomic level. Longer-term shifts are caused by electrical changes in the circuit elements, often referred to as "aging." This drift tends to occur at a reduced rate as compared to initial drift, and to further reduce over time. It is therefore often specified as drift/$\sqrt{\text{khr}}$. Voltage references tend to age more quickly at higher temperatures.

**Thermal Hysteresis**

This often-overlooked specification can also be a dominant source of error. It is mechanical in nature, and is the result of changing die stress due to thermal cycling. Hysteresis can be observed as a change in output voltage at a given temperature after a large temperature cycle. It is independent of temperature coefficient and time drift, and reduces the effectiveness of initial voltage calibration.

Most references tend to vary around a nominal output voltage during subsequent temperature cycles, so thermal hysteresis is usually limited to a predictable maximum value. Each manufacturer has their own method for specifying this parameter, so typical values can be misleading. Distribution data, as provided in data sheets such as the LT1790 and LTC6652, is far more useful when estimating output voltage error.

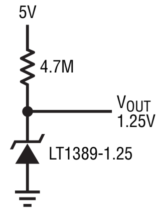


Figure 3. Shunt voltage reference

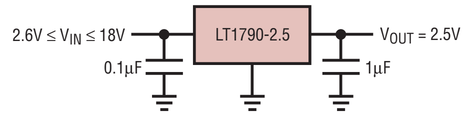


Figure 4. Series voltage reference

### Other Specifications

Additional specifications that may be important, depending on application requirements include:

- ❑ Voltage Noise
- ❑ Line Regulation/PSRR
- ❑ Load Regulation
- ❑ Dropout Voltage
- ❑ Supply Range
- ❑ Supply Current

## Reference Types

The two main types of voltage reference are shunt and series. See Table 2 for a list of Linear Technology series and shunt voltage references.

### Shunt References

The shunt reference is a 2-terminal type, usually designed to work over a specified range of currents. Though most shunts are of the bandgap type and come in a variety of voltages, they can be thought of and are as simple to use as a Zener diode.

The most common circuit ties one terminal of the reference to ground and the other terminal to a resistor. The remaining terminal of the resistor is then tied to a supply. This becomes, in essence, a three terminal circuit. The shared reference/resistor terminal is the output. The resistor must be chosen such that the minimum and maximum currents through the reference are within the specified range over the entire supply range and load current range. These references are quite easy to design with, provided the supply voltage and load current do not vary much. If either, or both, may change substantially, then the resistor must be chosen to accommodate this variance, often forcing the circuit to dissipate significantly more power than required for the nominal case. It can be considered to function like a class A amplifier, in that sense.

Advantages of shunt references include simple design, small packages and good stability over wide current and load conditions. In addition, they are easily designed as negative voltage references and can be used with very high supply voltages, as the external resistor holds off most of the potential, or very low supplies, as the output can be as little as a few millivolts below the supply. Linear Technology offers shunt products including the LT1004, LT1009, LT1389, LT1634, LM399 and LTZ1000. A typical shunt circuit can be seen in Figure 3.

### Series References

Series references are three (or more) terminal devices. They are more like low dropout (LDO) regulators, so they have many of the same advantages. Most notably, they consume a relatively fixed amount of supply current over a wide range of supply voltages, and they only conduct load current when the load demands it. This makes them ideal for circuits with large changes in supply voltage or load current. They are especially useful in circuits with very large load currents as there is no series resistor between the reference and supply.

Series products available from Linear Technology include the LT1460, LT1790, LT1461, LT1021, LT1236, LT1027, LTC6652, LT6660, and many others. Products such as the LT1021 and LT1019 may be operated either as a shunt or a series voltage reference. A series reference circuit is illustrated in Figure 4.

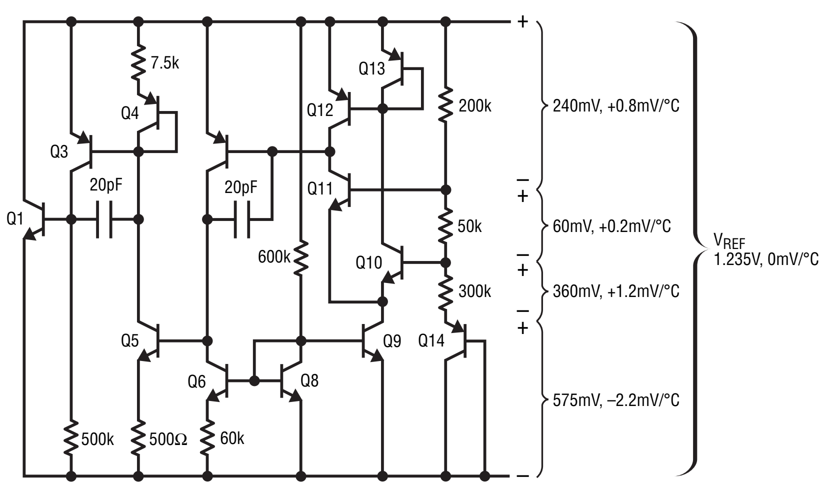


Figure 5. A bandgap circuit is designed for a theoretically zero temperature coefficient.

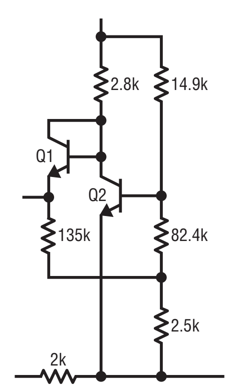


Figure 6. A 200mV reference circuit

## Reference Circuits

There are many ways to design a voltage reference IC. Each has specific advantages and disadvantages.

### Zener-Based References

The buried Zener type reference is a relatively simple design. A Zener (or avalanche) diode has a predictable reverse voltage that is fairly constant over temperature and very constant over time. These diodes are often very low noise and very stable over time if held within a small temperature range, making them useful in applications where changes in the reference voltage must be as small as possible.

This stability can be attributed to the relatively small number of components and die area as compared to other types of reference circuits, as well as the careful construction of the Zener element. However, relatively high variances in initial voltage and temperature drift are common. Additional circuitry may be added to compensate these imperfections, or to provide a range of output voltages. Both shunt and series references use Zener diodes.

Devices like the LT1021, LT1236 and LT1027 use internal current sources and amplifiers to regulate the Zener voltage and current to increase stability, as well as to provide various output voltages such as 5V, 7V and 10V. This additional circuitry makes the Zener diode more compatible with a wide variety of application circuits, but requires some additional supply headroom and may cause additional error.

Alternatively, the LM399 and LTZ1000 use internal heating elements and additional transistors to stabilize the temperature drift of the Zener diode, giving the best combination of temperature and time stability. In addition, these Zener-based products have extraordinarily low noise, giving the best possible performance. The LTZ1000 exhibits 0.05ppm/°C temperature drift, $2\mu V/\sqrt{kHr}$ long term stability and $1.2\mu V_{P-P}$ noise. To give some perspective, in a laboratory instrument, the total uncertainty in the LTZ1000's reference voltage due to noise and temperature would be only about 1.7ppm plus a fraction of 1ppm per month due to aging.

Table 2. Voltage references available from Linear Technology

| Type | Part | Description |
|---|---|---|
| Series | LT1019 | Precision Bandgap |
| | LT1021 | Precision Low Noise Buried Zener |
| | LT1027 | Precision 5V Buried Zener |
| | LT1031 | Precision Low Noise/Low Drift 10V Zener |
| | LT1236 | Precision Low Noise Buried Zener |
| | LT1258 | Micropower LDO Bandgap |
| | LT1460 | Micropower Precision Bandgap |
| | LT1461 | Micropower Ultra-Precision Bandgap |
| | LT1790 | Micropower Low Dropout Bandgap |
| | LT1798 | Micropower LDO Bandgap |
| | LT6650 | Micropower 400mV/Adjustable Bandgap |
| | LTC6652 | Precision Low Noise LDO Bandgap |
| Shunt | LM129 | Precision 6.9V Buried Zener |
| | LM185 | Micropower 1.2V/2.5V Zener |
| | LM399 | Precision 7V Heated Zener |
| | LT1004 | Micropower 1.2V/2.5V Bandgap |
| | LT1009 | Precision 2.5V Bandgap |
| | LT1029 | 5V Bandgap |
| | LT1034 | Micropower Dual (1.2V Bandgap/7V Zener) |
| | LT1389 | Nanopower Precision Bandgap |
| | LT1634 | Micropower Precision Bandgap |
| | LTZ1000 | Ultra-Precision Heated Zener |

### Bandgap References

While Zener diodes can be used to make very high performance references, they lack flexibility. Specifically, they require supply voltages above 7V and they offer relatively few output voltages. In contrast, bandgap references can produce a wide variety of output voltages with little supply headroom—often less than 100mV. Bandgap references can be designed to provide very precise initial output voltages and low temperature drift, eliminating the need for time-consuming in-application calibration.

Bandgap operation is based on a basic characteristic of bipolar junction transistors. Figure 5 shows a simplified version of the LT1004 circuit, a basic bandgap. It can be shown that a mismatched pair of bipolar junction transistors has a difference in $V_{BE}$ that is proportional to temperature. This difference can be used to create a current that rises linearly with temperature. When this current is driven through a resistor and a transistor, the change over temperature of the base-emitter voltage of the transistor cancels the change in the voltage across the resistor if it is sized properly. While this cancellation is not completely linear, it can be compensated with additional circuitry to yield very low temperature drift.

The math behind the basic bandgap voltage reference is interesting in that it combines known temperature coefficients with unique resistor ratios to produce a voltage reference with theoretically zero temperature drift. Figure 5 shows two transistors scaled so that the emitter area of Q10 is 10-times that of Q11, while Q12 and Q13 hold their collector currents equal. This creates a known voltage between the bases of the two transistors of:

$$\Delta V_{BE} = \frac{kT}{q} \bullet \ln\left(\frac{\text{AREA Q10}}{\text{AREA Q11}}\right)$$

where k is the Boltzmann constant in J/kelvin ($1.38 \times 10^{-23}$), T is temperature in kelvin (273 + T(°C)) and q is the charge of an electron in coulombs ($1.6 \times 10^{-19}$). At 25°C, kT/q has a value of 25.7mV with a positive temperature coefficient of 86μV/°C. $\Delta V_{BE}$ is this voltage times ln(10), or 2.3, for a 25°C voltage of approximately 60mV with a tempco of 0.2mV/°C.

Applying this voltage to the 50k resistor tied between the bases creates a current that is proportional to temperature. This current biases a diode, Q14 with a 25°C voltage of 575mV with a –2.2mV/°C temperature coefficient. Resistors are used to create voltage drops with positive tempcos, which are added to the Q14 diode voltage, thus producing a reference voltage potential of approximately 1.235V with theoretically 0mV/°C temperature coefficient. These voltage drops are shown in Figure 5. The balance of the circuit provides bias currents and output drive.

Linear Technology produces a wide variety of bandgap references, including the LT1460, a small and inexpensive precision series reference, the LT1389, an ultralow power shunt reference, and the LT1461 and LTC6652, which are very high precision, low drift references. Available output voltages include 1.2V, 1.25V, 2.048V, 2.5V, 3.0V, 3.3V, 4.096V, 4.5V, 5V and 10V. These reference voltages can be provided over a wide range of supplies and load conditions with minimal voltage and current overhead. Products may be very precise, as with the LT1461, LT1019, LTC6652 and LT1790; very small, as with the LT1790 and LT1460 (SOT23), or LT6660 in a 2mm × 2mm DFN package; or very low power, such as the LT1389, which requires only 800nA. While Zener references often have better performance in terms of noise and long term stability, new bandgap references such as the LTC6652, with 2ppm peak-to-peak noise (0.1Hz to 10Hz) are narrowing the gap.

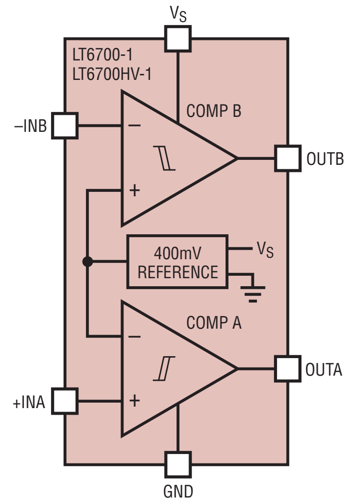


**Figure 7. The LT6700 allows comparisons with thresholds as low as 400mV.**

## Fractional Bandgap References

These are references based on the temperature characteristics of bipolar transistors, but with output voltages that may be as low as a few millivolts. They are useful for very low voltage circuits, especially in comparator applications where the threshold must be less than a conventional bandgap voltage (approximately 1.2V).

Figure 6 shows the core circuit from the LM10, which combines elements that are proportional and inversely proportional to temperature in a similar fashion to the normal bandgap reference to obtain a constant 200mV reference. A fractional bandgap usually uses a $\Delta V_{BE}$ to generate a current that is proportional to temperature, and a $V_{BE}$ to generate a current that is inversely proportional. These are combined in the proper ratio in a resistor element to generate a temperature-invariant voltage. The size of the resistor may be varied to alter the reference voltage without affecting the temperature characteristic. This differs from a traditional bandgap circuit in that the fractional bandgap circuit combines currents, while the traditional circuits tend to combine voltages, usually a base-emitter voltage and an I•R with opposite TC.

Fractional bandgaps like the LM10 circuit are based in part on a subtraction as well. The LT6650 has a 400mV reference of this type, combined with an amplifier. This allows the reference voltage to be altered by changing the gain of the amplifier, and gives a buffered output. Any output voltage from 0.4V to a few millivolts below the supply voltage can be generated with this simple circuit. In a more integrated solution, the LT6700 (Figure 7) and LT6703 combine a

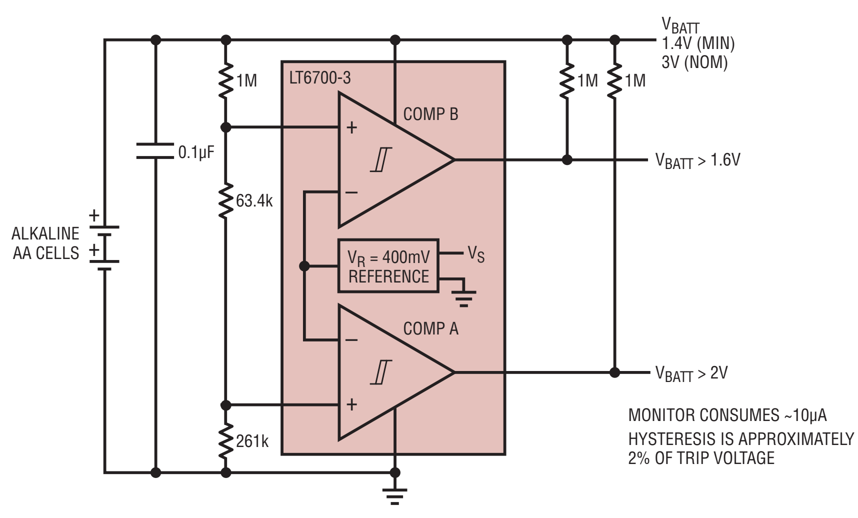


**Figure 8. Higher thresholds are set by dividing the input voltage.**

400mV reference with comparators, and can be used as voltage monitors or window comparators. The 400mV reference allows monitoring of small input signals, which decreases the complexity of monitor circuits and enables monitoring of circuit elements working on very low supplies as well. For larger thresholds, a simple resistor divider may be added (Figure 8). Each of these products is available in a small footprint package (SOT23), consumes low power (less than 10µA) and works on a wide supply range (1.4V to 18V). In addition, the LT6700 is available in a 2mm × 3mm DFN package and the LT6703 is available in a 2mm × 2mm DFN package.

## Choosing a Reference

So, now, with all those options, how do you choose the right reference for your application? Here are a few hints that can narrow the range of options:

- ❑ **Is the supply voltage very high?** Choose a shunt.
- ❑ **Does the supply voltage or load current vary widely?** Choose a series.
- ❑ **Require high power efficiency?** Choose a series.
- ❑ **Figure your real-world temperature range.** Linear Technology provides guaranteed specifications and operation over various temperature ranges including 0°C to 70°C, –40°C to 85°C and –40°C to 125°C.
- ❑ **Be realistic about required accuracy.** It is important to understand the precision required by the application. This will help identify critical specifications. With the requirement in mind, multiply temperature drift by the specified temperature range. Add initial accuracy error, thermal hysteresis, and long term drift over the intended product life. Remove any terms that will be factory calibrated or periodically recalibrated. This gives an idea of total accuracy. For the most demanding applications, noise, line regulation and load regulation errors may also be added. As an example, a reference with 0.1% (1000ppm) initial accuracy error, 25ppm/°C temperature drift over –40°C to 85°C, 200ppm thermal hysteresis, 2ppm peak-to-peak noise and $50ppm/\sqrt{kHr}$ time drift would have a total uncertainty of over 4300ppm at the time the circuit is built. This uncertainty increases by 50ppm in the first 1000 hours the circuit is powered. The initial accuracy may be calibrated, reducing the error to $3300ppm + 50ppm \bullet \sqrt{(t/1000hours)}$.

***Linear Technology offers a wide variety of voltage reference products. These include both series and shunt references—using Zeners, bandgaps and other schemes. References are available in multiple performance and temperature grades, as well as in nearly every conceivable package type.***

- ❑ **What is the real supply range?** What is the maximum expected supply voltage? Will there be fault conditions such as battery load dump or hot-swap inductive supply spikes that the reference IC must withstand? This may significantly reduce the number of viable choices.
- ❑ **How much power can the reference consume?** References tend to fall into a few categories: more than 1mA, ~500µA, <300µA, <50µA, <10µA, <1µA.
- ❑ **How much load current?** Will the load draw substantial current or produce current that the reference must sink? Many references can provide only small currents to the load and few can absorb substantial current. The load regulation specification is a good guide.
- ❑ **How much room do you have?** References come in a wide variety of packages, including metal cans, plastic packages (DIP, SOIC, SOT) and very small packages, including the LT6660 in a 2mm × 2mm DFN. There is a widely held view that references in larger package sizes have less error due to mechanical stress than smaller packages. While it is true that some references may give better performance in larger packages, there is evidence that suggests performance difference has little to do directly with the package size. It is more likely that because smaller dice are used for products that are offered in smaller packages, some performance tradeoffs must be made to fit the circuit on the die. Usually, the package's mounting method makes a more significant performance difference than the actual package—careful attention to mounting methods and locations can maximize performance. Also, devices with smaller footprints can show reduced stress when a PCB bends compared to devices with larger footprints. This is discussed in detail in application note AN82, "Understanding and Applying Voltage References," available from Linear Technology.

## Conclusion

Linear Technology offers a wide variety of voltage reference products. These include both series and shunt references designed with Zeners, bandgaps and other types. References are available in multiple performance and temperature grades and nearly every conceivable package type. Products range from the highest precision available to small and inexpensive alternatives. With a vast arsenal of voltage reference products, Linear Technology's voltage references meet the needs of almost any application.

See also Linear Technology's application note AN82 "Understanding and Applying Voltage References," available at www.linear.com.