



Application Notes

AN-18

THERMOMETER APPLICATIONS OF THE REF-02

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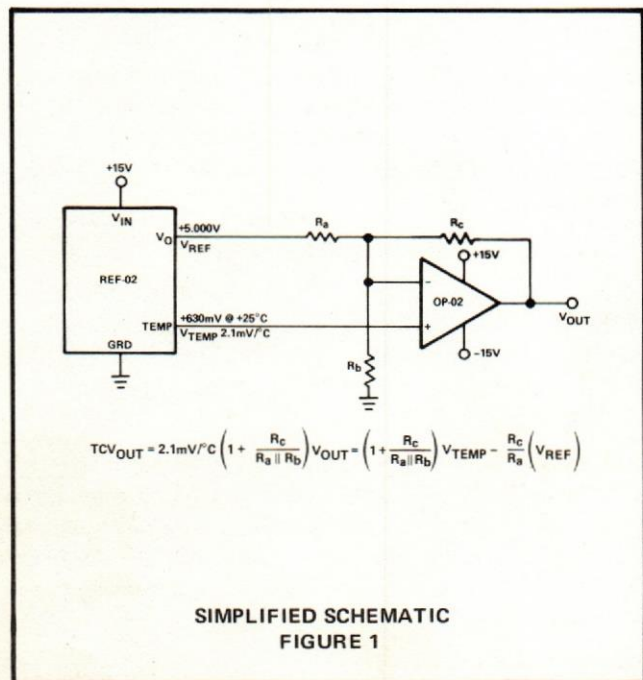
INTRODUCTION

This application note describes electronic thermometer applications of the REF-02 +5V Voltage Reference where the voltage output is a direct measurement of temperature in °C or in °F. These applications use the predictable 2.1mV/°C TEMP output voltage temperature coefficient of the REF-02, a byproduct of a bandgap voltage reference design. Thermometer applications are described first followed by a discussion of bandgap voltage reference theory.

THERMOMETER ESSENTIALS

In addition to a highly linear temperature sensitive component, electronic thermometers should have the following characteristics:

- 1) Convenient scaling such as 10mV/°C, 100mV/°C, or 10mV/°F.
- 2) Direct voltage readings such as -0.55V at -55°C, 0V at 0°C, and +1.25V at +125°C.
- 3) Room temperature calibration.



BASIC CIRCUIT IMPLEMENTATION

The simplified schematic in Fig. 1 shows the basic thermometer connections. An operational amplifier, three resistors, and the +5.000V output of the REF-02 function together to level shift and amplify VTEMP allowing VOUT to read in the desired manner. The expression for VOUT is:

$$\text{Eq. 1) } V_{OUT} = \left(1 + \frac{R_c}{R_a \parallel R_b}\right) V_{TEMP} - \frac{R_c}{R_a} (V_{REF})$$

The first term is the gain of the circuit with VREF equal to 0V; the second term is the gain of the circuit with VTEMP equal to 0V. Differentiating Eq. 1 with respect to temperature gives the slope, S, of the output-versus-temperature curve:

$$\begin{aligned} \text{Eq. 2) } \frac{dV_{OUT}}{dT} &= S = m \left(1 + \frac{R_c}{R_a \parallel R_b}\right) \\ &= 2.1\text{mV}/^\circ\text{C} \left(1 + \frac{R_c}{R_a \parallel R_b}\right) \end{aligned}$$

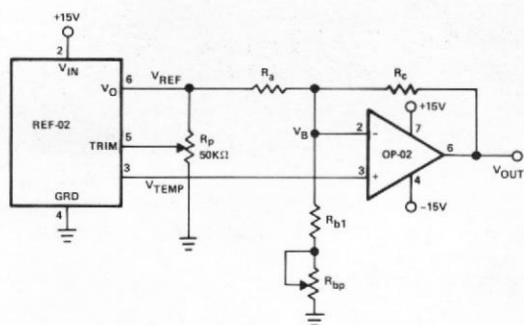
where $m = \text{TCV}_{TEMP}$

Thus, the ratio of R_c to $R_a \parallel R_b$ sets the slope of VOUT, and the ratio of R_c to R_a and VREF set the initial output value at 25°C. Table I lists typical scaling ratios for different output scales

TEMPERATURE SCALING RATIOS

$V_{REF} = 5.000\text{V}$, $V_{TEMP} = 630\text{mV @ } 25^\circ\text{C}$, $\text{TCV}_{TEMP} = 2.1\text{mV}/^\circ\text{C}$			
$V_{OUT @ 25^\circ\text{C}}$ (77°F)	TCV_{OUT} (Slope)	$\frac{R_c}{R_a}$	$\frac{R_c}{R_a \parallel R_b}$
250mV	10mV/°C	0.55	3.76
2.5V	100mV/°C	5.50	46.6
770mV	10mV/°F	0.926	7.57

TABLE I



COMPLETE SCHEMATIC
FIGURE 2

COMPLETE CIRCUIT

Two potentiometers, R_p and R_{bp} , have been added to the circuit for precise calibration and to allow for the $\pm 1\%$ resistor tolerances. V_{REF} is adjusted by R_p to set the V_{OUT} value at $+25^\circ\text{C}$ (77°F); the ratio of R_c to $R_a \parallel R_b$ is adjusted by R_{bp} to set the slope of V_{OUT} versus temperature. Resistor values for typical output scales are shown in Table II.

RESISTOR VALUES

TCV _{OUT} SLOPE (S)	10mV/ $^\circ\text{C}$	100mV/ $^\circ\text{C}$	10mV/ $^\circ\text{F}$
TEMPERATURE RANGE	-55° to $+125^\circ\text{C}$	-55° to $+125^\circ\text{C}$	-67°F to $+257^\circ\text{F}$
OUTPUT VOLTAGE RANGE	-0.55V to $+1.25\text{V}$	-5.5V to $+12.5\text{V}^*$	-0.67V to $+2.57\text{V}$
ZERO SCALE	0V @ 0°C	0V @ 0°C	0V @ 0°F
R_a ($\pm 1\%$ resistor)	9.09K Ω	15K Ω	7.5K Ω
R_{b1} ($\pm 1\%$ resistor)	1.5K Ω	1.82K Ω	1.21K Ω
R_{bp} (Potentiometer)	200 Ω	500 Ω	200 Ω
R_c ($\pm 1\%$ resistor)	5.11K Ω	84.5K Ω	8.25K Ω

*For 125°C operation, the op amp output must be able to swing to $+12.5\text{V}$; increase V_{IN} to $+18\text{V}$ with $+15\text{V}$ if this is a problem.

TABLE II

CALIBRATION CONDITIONS

All calibration is conducted in free air. Heatsinking of the REF-02 is unnecessary and is undesirable. The small (2°C) rise in chip temperature of the REF-02 above ambient temperature serves as an error-cancelling factor of some second order effects internal to the REF-02 design. The calibration procedure which follows assumes free air — no heatsinking — calibration.

CALIBRATION PROCEDURE

Calibration is performed at ambient temperature with two adjustments using the following procedure:

Step 1: Measure and record V_{TEMP} and T_A in $^\circ\text{C}$.

Step 2: Calculate the calibration ratio "r" using Eq. 3:

$$\text{Eq. 3) } r \equiv \frac{R_a \parallel R_b}{R_c + R_a \parallel R_b} = \frac{V_{TEMP} \text{ in mV}}{S(T_A + 273)}$$

Where $S = \text{TCV}_{OUT}$, T_A = ambient temperature in $^\circ\text{C}$

Step 3: Turn power off, short V_{REF} terminal to ground, and apply a precise 100mV to the V_{OUT} terminal.

Step 4: Adjust R_{bp} so that $V_B = r(100\text{mV})$; remove short.

Step 5: Turn power on; adjust R_p so that V_{OUT} equals the correct value at ambient temperature.

The system is now calibrated.

CALIBRATION EXAMPLE

Here is an example at $T_A = 25^\circ\text{C}$, $S = 10\text{mV}/^\circ\text{C}$, and $V_{TEMP} = 632\text{mV}$:

Step 1: $V_{TEMP} = 632\text{mV}$, $T_A = 25^\circ\text{C}$.

Step 2: Using Eq. 3:

$$r = \frac{V_{TEMP}}{S(T_A + 273)} = \frac{632}{10(25 + 273)} = \frac{632}{2980} = 0.2121$$

Step 3: Apply 100.00mV to V_{OUT} with power off and V_{REF} connected to ground.

Step 4: Adjust R_{bp} so that $V_B = r(100\text{mV}) = 21.21\text{mV}$

Step 5: Turn power on and adjust R_p so that V_{OUT} equals $+0.25\text{V}$.

The system is now calibrated.

TRANSDUCER ERROR FACTORS

Error terms are threefold:

1. Slope errors — Deviations from nominal slope. For example, if the slope is $10.04\text{mV}/^\circ\text{C}$ instead of $10.00\text{mV}/^\circ\text{C}$, the accuracy due to the slope error is 0.4%.
2. Linearity errors — Deviations in V_{TEMP} versus temperature from straight line performance, a change in V_{TEMP} slope with temperature.
3. Offset error — V_{OUT} deviations due to changes in V_{REF} with temperature.

Since these errors are grade dependent, Table III is provided as an aid in specifying the correct combination of components for a given application. Offset error can be eliminated by using one REF-02 as a temperature sensor only and another REF-02 (operated at a constant temperature) as V_{REF} .

TRANSDUCER PERFORMANCE

Typical system accuracy is $\pm 0.5\%$ over the -55° to $+125^\circ\text{C}$ range of a REF-02A. For example, when calibrated at $+25^\circ\text{C}$, the reading of V_{OUT} at $+105^\circ\text{C}$ may be 105.4°C , a deviation of 0.5% of the 80° temperature change ($+25^\circ\text{C}$ to $+105^\circ\text{C}$).

Although the REF-02 is guaranteed to perform over the -55° to $+125^\circ\text{C}$ range only, operation beyond those limits is possible. A large number of devices were measured and found to be functioning satisfactorily over the -150°C to $+170^\circ\text{C}$ range, and there was only a slight degradation in accuracy.

REMOTE APPLICATIONS

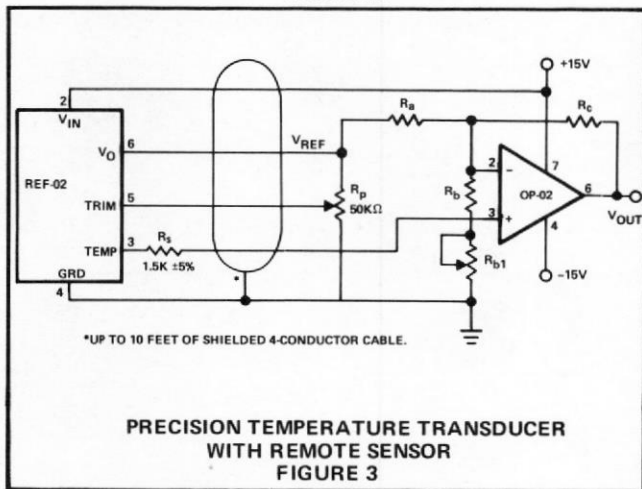
In many applications, the sensor must be located some distance away from the measurement circuitry. One precaution must be taken with the REF-02: a 1.5K Ω resistor

should be connected between pin 3 (TEMP) and its associated cable conductor to isolate this pin from cable capacitances. Remote application of the transducer is illustrated in Fig. 3 with R_s , the isolation resistor.

TYPICAL TRANSDUCER PERFORMANCE VS. GRADE

GRADE PARAMETER	REF-02A	REF-02	REF-02E	REF-02H	REF-02C
TEMPERATURE RANGE	-55° to +125°C	-55° to +125°C	0° to +70°C	0° to +70°C	0° to +70°C
SLOPE ERROR	±0.30%	±0.40%	±0.25%	±0.35%	±0.45%
TCVTEMP ERROR	±0.10%	±0.12%	±0.08%	±0.10%	±0.15%
OFFSET ERROR	±0.15%	±0.40%	±0.10%	±0.30%	±0.60%
RMS ERROR SUM	±0.35%	±0.58%	±0.28%	±0.47%	±0.76%
TYPICAL ACCURACY	0.50%	0.75%	0.40%	0.60%	0.90%
OP-02 GRADE RECOMMENDED	OP-02A	OP-02	OP-02E	OP-02C	OP-02C

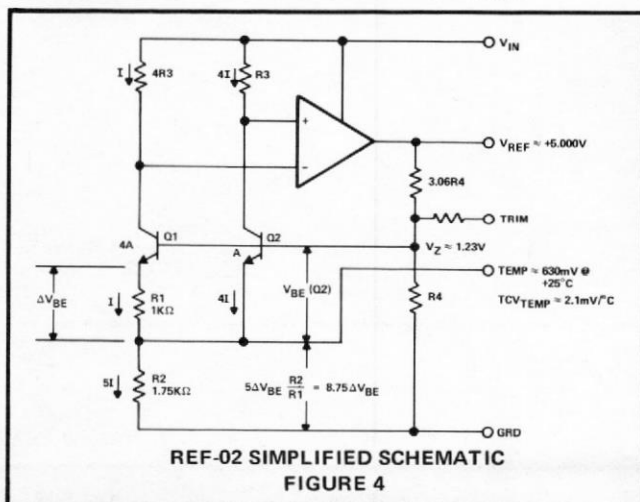
TABLE III



TRANSDUCER SUMMARY

The accuracies indicated compare quite favorably to traditional temperature measurement methods such as thermocouples and thermistors. Ease-of-use, low cost, and high accuracy make this new bandgap method of temperature measurement attractive in a wide range of applications.

The following section describes the bandgap principle in theory and its use in the internal REF-02 design.



BANDGAP REFERENCE THEORY

Bandgap voltage references [1], [2], [3], use predictable relationships from semiconductor physics to generate a constant voltage. The base-emitter voltage of a transistor (V_{BE}) has a processing and current density dependent negative temperature coefficient of about $-2.1\text{mV}/^\circ\text{C}$. Another well known relationship with a positive temperature coefficient is the difference between base-emitter voltages of two transistors operated at different current densities:

$$\text{Eq. 4) } \Delta V_{BE} = \frac{kT}{q} \log_e \left(\frac{J_2}{J_1} \right), \text{ where}$$

k = Boltzmann's constant = 1.38×10^{-23} joules/ $^\circ\text{K}$

T = absolute temperature, $^\circ\text{K}$

q = charge of an electron = 1.6×10^{-19} coulomb

J = current density

When ΔV_{BE} is amplified and added to V_{BE} , a voltage reference with zero temperature coefficient results if the sum (V_Z) of these two terms equals the linearly-extrapolated band-gap voltage of silicon (V_{go}) at 0°K or -273°C ; $V_{go} = 1.205\text{V}$. A more exact calculation, see reference [2], will show that V_Z will have zero temperature coefficient if:

$$\text{Eq. 5) } V_Z = V_{go} + \frac{kT}{q} = 1.230\text{V} @ +25^\circ\text{C}$$

The circuit in Fig. 4 generates a ΔV_{BE} of 72mV at 25°C by making the current density of Q2 16 times greater than Q1. Q2 has four times the current of Q1, and Q1 has four times the emitter area of Q2. A ΔV_{BE} of 72mV appears across $R1$ and is amplified by 8.75 (becoming the TEMP output) and is added to V_{BE} (Q2) to produce a nearly constant V_Z of 1.23V . The $-2.1\text{mV}/^\circ\text{C}$ of TCV_{BE} is cancelled by the $+2.1\text{mV}/^\circ\text{C}$ of TCV_{TEMP} ; and V_Z is amplified by 4.06 to produce an output V_{REF} of 5.000V .

REF-02 TYPICAL NODAL VOLTAGES

TEMPERATURE VOLTAGE	$T_A = -75^\circ\text{C}$ ($T_J = 200^\circ\text{K}$)	$T_A = +25^\circ\text{C}$ ($T_J = 300^\circ\text{K}$)	$T_A = +125^\circ\text{C}$ ($T_J = 400^\circ\text{K}$)
$\Delta V_{BE} = \frac{kT}{q} \log_e 16$	48mV	72mV	96mV
$V_{TEMP} = 8.75 \Delta V_{BE}$	420mV	630mV	840mV
$V_{BE} (Q2)$	810mV	600mV	390mV
$V_Z \approx V_{BE} + V_{TEMP}$	1.23V	1.23V	1.23V
$V_{REF} \approx 1 + \frac{3.06R4}{R4} \approx 4.06 V_Z$	5.00V	5.00V	5.00V

TABLE IV

CONCLUSION

The REF-02, by using a bandgap design, provides both a stable +5V reference voltage output and an additional output voltage directly proportional to temperature. Accurate electronic thermometers reading in °C or in °F can be constructed at low cost for a wide variety of temperature monitoring and controlling applications.

REFERENCES

- [1] "New Developments in IC Voltage Regulators"
R. J. Widlar
IEEE Journal of Solid-State Circuits
Volume sc-6, Number 1, February 1971.
- [2] "A Precision Reference Voltage Source"
K. E. Kuijk
IEEE Journal of Solid-State Circuits
Volume sc-8, Number 3, June 1973.
- [3] "A Simple Three-Terminal IC Bandgap Reference"
A. P. Brokaw
1974 IEEE International Solid-State Circuits
Conference Digest of Technical Papers.

APPLICATION NOTES AVAILABLE UPON REQUEST

- | | |
|---|---|
| AN-6 "A Low Cost, High-Performance Tracking A/D Converter" | AN-13 "The OP-07 Ultra-Low Offset Voltage Op Amp—A Bipolar Op Amp That Challenges Choppers, Eliminates Nulling" |
| AN-10 "Simple Precision Millivolt Reference Uses No Zeners" | AN-14 "Interfacing Precision Monolithics Digital-To-Analog Converters With CMOS Logic" |
| AN-11 "A Low Cost, Easy-To-Build Successive Approximation Analog-To-Digital Converter" | AN-15 "Minimization of Noise in Operational Amplifier Applications" |
| AN-12 "Temperature Measurement Method Based On Matched Transistor Pair Requires No Reference" | AN-16 "Low Cost, High Speed Analog-To-Digital Conversion with the DAC-08" |
| | AN-17 "DAC-08 Applications Collection" |

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