Oven-Compensated, Buried Zener, 6.62 V Voltage Reference

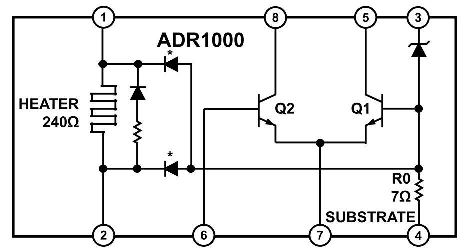
FEATURES

- High long-term stability
- 0.5 ppm/year long-term drift, typical (after first 3000 hours)
- Low Zener reference noise: 0.14 ppm p-p (0.9 μV p-p)
- Low temperature coefficient: <0.2 ppm/°C
- On-chip heater and temperature sensor
- Specified for −40°C to +125°C operation
- Pin-compatible upgrade to LTZ1000

APPLICATIONS

- High accuracy instrumentation
- Multimeters
- Weigh scales
- Electric balance
- Automatic test equipment
- Metrology equipment
- Standard cells
- Calibrators

FUNCTIONAL BLOCK DIAGRAM



*SUBSTRATE TO NEPI DIODE.

NOTES
1. PIN 4 IS THE SUBSTRATE AND IS CONNECTED TO THE CASE.

Figure 1.

GENERAL DESCRIPTION

The ADR1000 is a 6.62 V, output highly stable, oven-controlled, buried Zener reference component built on an Analog Devices, Inc., proprietary bipolar process and is a pin-compatible replacement for the LTZ1000. Included on the chip is a buried Zener reference, a heater resistor for temperature stabilization, and a temperature sensing transistor. External circuitry is used to set the operating currents and the temperature of the reference, allowing the maximum flexibility to achieve maximum long-term stability and minimum noise.

The ADR1000 application circuit can achieve a temperature coefficient of <0.2 ppm/°C and a long-term drift of 0.5 ppm per year (typical) after the first 3000 hours when properly implemented with the recommended external circuitry shown in Figure 9 and with the recommended layout.

The low long-term drift of the ADR1000 is well suited for any application that must maintain accuracy over long calibration intervals or product lifetime. The low thermal drift ensures the output is constant with temperature variation because the on-chip heater of the ADR1000 maintains a constant temperature higher than the expected ambient range.

The ADR1000 is specified for operation over the extended industrial temperature range of −40°C to +125°C. To obtain the optimal thermal drift performance, the temperature set point of the heater needs to be 10°C higher than the maximum ambient temperature to provide optimum stability of the buried Zener reference.

The ADR1000 comes packaged in an industry-standard, 8-pin TO-99 metal can package that is hermetically sealed to resist the effects of humidity.

Table 1. Related Products

Model	Output Voltage (V)	Initial Accuracy (mV)
ADR1000	6.62	±50
LTZ1000	7.2	−200, +300
LM399	6.95	−200, +350
ADR1399	7.05	−300 to +250

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REVISION HISTORY

3/2022—Revision B: Initial Version

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SPECIFICATIONS

ELECTRICAL CHARACTERISTICS

T_A = 25°C, unless otherwise noted.

Table 2.

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
ZENER REFERENCE VOLTAGE (V_{BZ1} + V_{BEQ1})[1]	V_{REF}	Zener current (I_{BZ1}) = 5 mA, CQ1 current (I_{CQ1}) = 100 µA	6.57	6.62	6.67	V
		I_{BZ1} = 1 mA, I_{CQ1} = 100 µA	6.54	6.59	6.64	V
ZENER LEAKAGE CURRENT	I_Z	Zener voltage (V_Z) = 5 V		1	1.5	µA
ZENER REFERENCE NOISE (V_Z + V_{BEQ1})	$e_{N\ p\text{-}p}$	I_{BZ1} = 5 mA, I_{CQ1} = 100 µA, 0.1 Hz < f < 10 Hz		0.14		ppm p-p
				0.9		µV p-p
	e_N	I_{BZ1} = 5 mA, I_{CQ1} = 100 µA				
		f = 0.1 Hz		300		nV/√Hz
		f = 10 Hz		30		nV/√Hz
		f = 1 kHz		24		nV/√Hz
HEATER RESISTANCE	R_{HTR}	Heater current (I_{HEATER}) = 1 mA	230	242	255	Ω
BREAKDOWN VOLTAGE						
Heater	BV_{HTR}	I_{HEATER} < 10 µA to Pin 4 (I_{ZSET})	70	80		V
Transistor Q1	BV_{CEO}	I_{CQ1} < 10 µA	15	18		V
Transistor Q2	BV_{CEO}	CQ2 current (I_{CQ2}) < 10 µA	28	39		V
CURRENT GAIN						
Q1	h_{FE_Q1}	I_{CQ1} = 100 µA, V_{CE} = 600 mV	280	400	520	A/A
Q2	h_{FE_Q2}	I_{CQ1} = 100 µA, V_{CE} = 600 mV	190	300	410	A/A
TEMPERATURE COEFFICIENT	TCV_{REF}	Using the circuit shown in Figure 9 with the recommended layout		<0.2		ppm/°C
THERMAL HYSTERESIS	ΔV_{REF_TH}	I_{BZ1} = 5 mA, I_{CQ1} = 100 µA, ΔT_A = 100°C		1		ppm
				6.62		µV
THERMAL RESISTANCE	θ_{JA}	Time = 5 minutes		216		°C/W
LONG-TERM DRIFT	ΔV_{REF_LTD}	I_{BZ1} = 5 mA, I_{CQ1} = 100 µA, T_A = 25°C, chip set temperature (T_{SET}) = 75°C				
		200 hours (early life drift)		8.9		ppm
		1000 hours		7.7		ppm
		2000 hours		6.6		ppm
		3000 hours		6.2		ppm
		1 year (after first 3000 hours)		0.5		ppm

[1] V_{BZ1} is the buried Zener diode voltage, and V_{BEQ1} is the base emitter voltage of the temperature compensating transistor.

ABSOLUTE MAXIMUM RATINGS

Table 3.

Parameter	Rating
Heater to Substrate (Pin 4)	40 V
Q1 Collector to Emitter	15 V
Q2 Collector to Emitter	28 V
Emitter to Base Reverse Bias (Q1 and Q2)	2 V
Substrate Forward Bias	0.1 V
Storage Temperature Range	−65°C to +150°C
Operating Temperature Range	−40°C to +125°C
Junction Temperature Range	−65°C to +150°C
Lead Temperature, Soldering (10 sec)	300°C
Electrostatic Discharge (ESD) Rating	
Human Body Model (HBM)	2 kV

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

THERMAL RESISTANCE

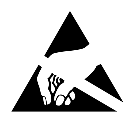
Thermal performance is directly linked to PCB design and operating environment. Close attention to PCB thermal design is required.

Table 4. Thermal Resistance[1]

Package Type	θ_{JA}	θ_{JC}	Unit
H-08			
1-Layer JEDEC Board	N/A[1]	N/A[1]	°C/W
2-Layer JEDEC Board	216	N/A[1]	°C/W

1 N/A means not applicable.

ESD CAUTION



ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

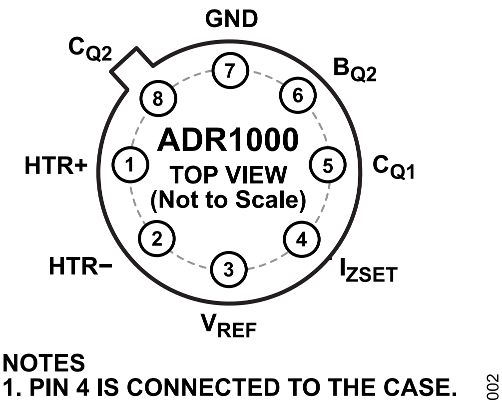


Figure 2. Pin Configuration

Table 5. Pin Function Descriptions

Pin No.	Mnemonic	Description
1	HTR+	Heater Positive. HTR+ must have a higher positive value than HTR− (Pin 2) and I_{ZSET} (Pin 4).
2	HTR−	Heater Negative. HTR− must have a higher positive value than I_{ZSET} (Pin 4) and must have equal or lower potential than HTR+ (Pin 1).
3	V_{REF}	Zener Positive. V_{REF} must have a higher positive value than I_{ZSET} (Pin 4).
4	I_{ZSET}	Substrate and Zener Negative. I_{ZSET} must have a higher positive value than GND (Pin 7).
5	C_{Q1}	Temperature Compensating Transistor Collector (Q1).
6	B_{Q2}	Temperature Sensing Transistor Base (Q2).
7	GND	Emitter of Sensing and Compensating Transistors.
8	C_{Q2}	Collector of Sensing Transistor (Q2).

TYPICAL PERFORMANCE CHARACTERISTICS

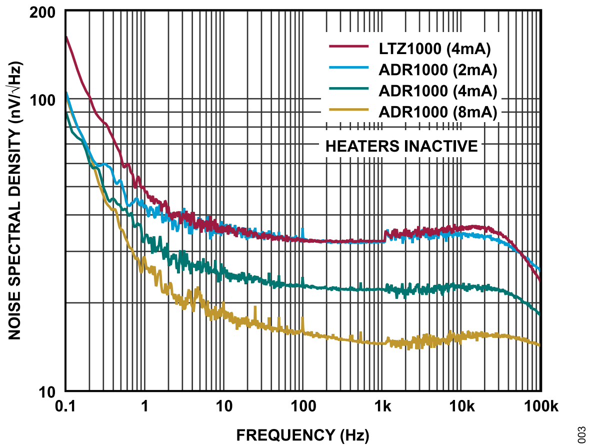


Figure 3. Noise Spectral Density vs. Frequency, LTZ1000 and ADR1000 with Various I_{BZ1}, I_{CQ1} = 100 μA (Heater Inactive)

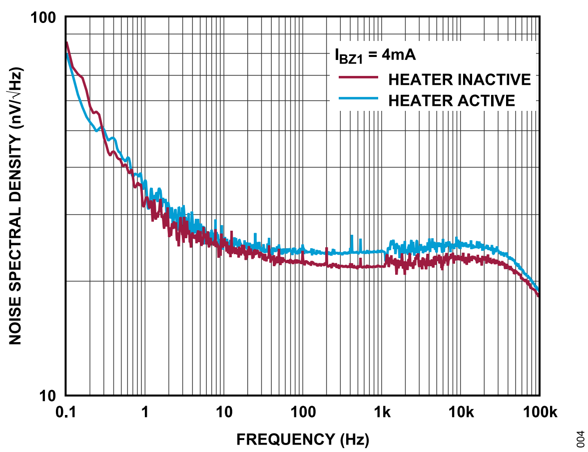


Figure 4. Noise Spectral Density vs. Frequency, Heater Active vs. Inactive, I_{BZ1} = 4 mA I_{CQ1} = 100 μA

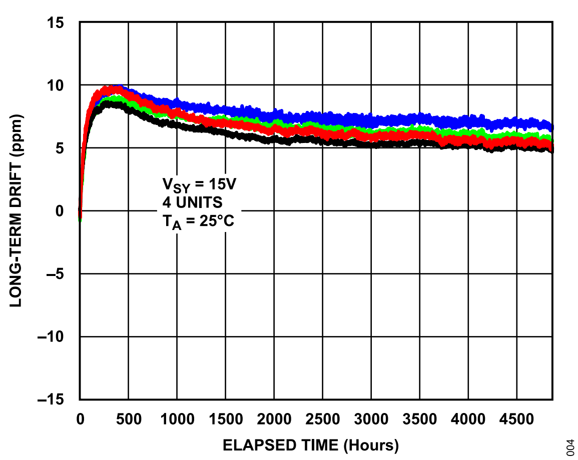


Figure 5. Long-Term Drift vs. Elapsed Time, T_{SET} = 75°C

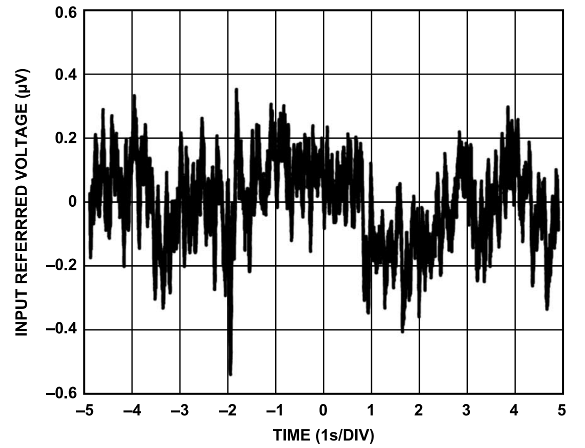


Figure 6. 0.1 Hz to 10 Hz Noise Peak to Peak, I_{CQ1} = 100 μA and I_{BZ1} = 5 mA

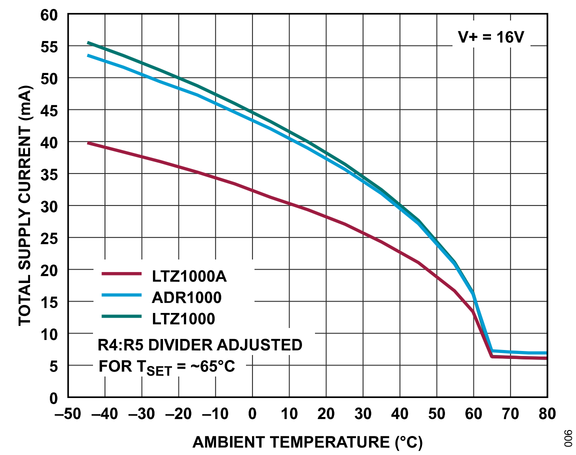


Figure 7. Total Supply Current vs. Ambient Temperature, ADR1000, LTZ1000, and LTZ1000A, Circuit of Figure 9 with R4:R5 Dividers Adjusted for T_{SET} = ~65°C

THEORY OF OPERATION

The ADR1000 consists of a buried Zener diode, a temperature compensating transistor, a temperature sensing transistor, and a heater resistor. The output reference voltage (V_{REF}) is formed by summing the buried Zener diode voltage (V_{BZ1}) and a temperature compensating transistor base emitter voltage (V_{BEQ1}), where the Zener diode temperature coefficient is approximately +2 mV/°C, and the transistor V_{BE} temperature coefficient is approximately −2 mV/°C. Referring to Figure 9, an external op amp (U3), in combination with an external resistor (R1), is used to set the Zener operating current as follows:

$$R1 = \frac{(0.658\,\text{V} - 0.0022 \times T_{SET})}{I_Z} - 7\,\Omega$$

where:
T_{SET} is the heated chip temperature.
I_Z is the desired Zener current.
0.658 V is the Q1 V_{BE} at 0°C.
7 Ω is the bulk resistance to the Zener anode.

With T_{SET} = 70°C and I_Z = 4 mA,

$$R1 = \frac{(0.658\,\text{V} - 0.002 \times 70)}{I_Z} - 7\,\Omega = 129.5\,\Omega$$

Note that because the 7 Ω bulk resistance (R0 in Figure 1) schematically appears under the Q1 base, it must be included in the calculation of I_Z. The primary performance implication of the buried Zener operating current is output voltage noise. The ADR1000 can achieve a total output noise of 0.14 ppm (0.9 µV p-p) in the 0.1 to 10 Hz frequency band when I_{BZ1} = 5 mA and I_{CQ1} = 100 µA, with the dominant noise source being the Zener diode. Increasing the current in the Zener (I_{BZ1}) reduces the reference noise by the inverse square root of the Zener current. A Zener bias current greater than 8 mA is not practical because power dissipation limits maximum ambient temperature. The ADR1000 applications circuit output noise spectral density has been measured over a range of Zener set currents (see Figure 3). The ADR1000 long-term drift (LTD) is characterized at a Zener current of I_{BZ1} = 5 mA and a Q1 current of I_{CQ1} = 100 µA, and results are shown in Figure 5.

SETTING THE OPERATING TEMPERATURE

The ADR1000 can regulate chip operating temperature to within a few millidegrees over a 100°C ambient temperature change. This means if the unheated reference temperature coefficient is 20 ppm/°C, then the theoretical heated temperature coefficient is well below 0.1 ppm/°C. This performance is difficult to achieve in a practical circuit (refer to the Avoiding Thermocouple Errors section for more information). The V_{BE} of Q2 is compared to a divided down copy of the 6.62 V reference voltage (see Figure 9). The 13 kΩ:1 kΩ divider sets the V_{BE} of the Q2 at around 474 mV. At room temperature, a V_{BE} of 474 mV does not provide enough collector current to satisfy the condition that the input terminals of U2 must be equal to within a few hundred microvolts. Thus, the noninverting input of U2 is pulled up until its inputs clamp or until its noninverting terminal hits V_{REF}. The voltage difference between the two inputs of U2 causes the output of U2 to pull up, increasing the amount of power dissipated in the on-chip heater. Because the transistor base emitter voltage has a negative temperature coefficient, the collector current of Q2 increases as the chip temperature rises, causing the op amp inputs to move closer together until the voltage drop across R3 satisfies the loop. The temperature at which the thermal loop is satisfied is the chip set temperature (T_{SET}).

Figure 7 shows the ADR1000 and LTZ1000A total supply current vs. the ambient temperature. Notice that the heater current has a square root dependence on the difference between the ambient temperature and the set temperature because the power dissipated in the heater is proportional to the square of the current. When the ambient temperature reaches the set temperature, the current in the heater goes to zero, and the chip temperature is no longer regulated.

THERMAL RESISTANCE

The ADR1000 uses a specialized epoxy die attachment to maximize the thermal isolation that reduces the power consumption required to achieve a given set temperature. At an ambient temperature of 10°C, the heater power consumption is approximately 35 mA^2 × 242 Ω = 300 mW, assuming that the heater supply current is the total supply current minus 5 mA for the Zener current and other components on the PCB (see Figure 7). For 300 mW dissipation in the heater, the internal temperature of the ADR1000 is elevated by 65°C, yielding a 216°C/W junction to ambient thermal impedance (θ_{JA}).

Table 6. Recommended Values for Varying the Set Temperature in 5° Increments

Estimate Set Temperature (°C)	R4 (Ω)	R5 (kΩ)	V_{BEQ2} (mV)
80	13 k + 316	1	464
75	13 k	1	474
70	13 k − 316	1	484
65	13 k − 632	1	494

THEORY OF OPERATION

HEATER HEADROOM CONSIDERATIONS

When colder ambient temperatures are combined with higher set temperatures, the heater drive NPN transistor (Q_{HTR}) and the op amp driving its base may need more headroom. For example, at −40°C, the heater current is approximately 45 mA, which, when multiplied by the 242 Ω heater resistance, raises Pin 1 (HTR+) to 10.9 V. A positive supply voltage (V+) set at 15 V results in 4.1 V headroom for Q_{HTR}. If characterization shows a marked increase in the temperature coefficient of the ADR1000 at lower ambient temperatures, the most likely culprit is not enough headroom for Q_{HTR}. This issue can be solved by either increasing V+ or by choosing a lower set temperature to reduce T_{RISE}. The following formula can be used to estimate the minimum heater supply voltage, V_{MIN}:

$$V_{MIN} = \sqrt{(T_{RISE}/(\theta_{JA} \times R_H))} \times R_H + V_{BEQHTR} + I_{BQHTR} \times 1\ \text{k}\Omega + V_{OUT\_ADA4084\text{-}1}$$

where:
T_{RISE} is the required temperature rise.
θ_{JA} is the package thermal resistance (216°/W).
R_H = 240 Ω. R_H is the resistance of the on-chip heater element.
V_{BEQHTR} is the base emitter voltage of Q_{HTR}, 900 mV, which is discrete transistor dependent.
I_{BQHTR} is the base current in the Q_{HTR}.
$V_{OUT\_ADA4084\text{-}1}$ is the positive headroom limitation, 1 V.

$$T_{RISE} = T_{SET} - T_{AMBIENT}$$

$$I_{BQHTR} \times 1\ \text{k}\Omega = (\sqrt{(T_{RISE}/(\theta_{JA} \times R_H))}/\beta) \times 1\ \text{k}\Omega$$

where β is the transistor current gain, assumed to be 100.

Figure 8 shows a plot of the approximate minimum heater supply voltage (V_{MIN}) vs. required temperature rise (T_{RISE}).

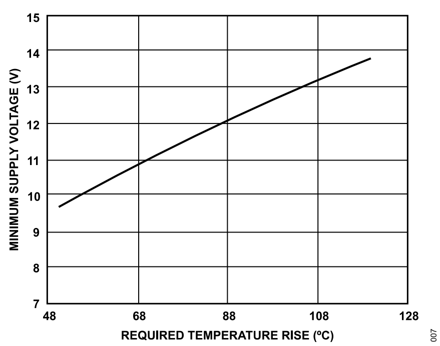


Figure 8. Minimum Supply Voltage vs. Required Temperature Rise

CHOOSING EXTERNAL OP AMPS

The ADA4084-x op amp is used with the ADR1000 evaluation board because it has a common-mode range that includes ground on a single supply, and because the output swings rail to rail. Ground sensing inputs ensure proper startup when input signals are both close to 0 V. Post startup, the ADA4084-x common mode remains at around 480 mV. Rail-to-rail output swing ensures that the heater voltage can be driven from 0 V to 1 V below the positive supply. One additional requirement is that the op amp not swing to exactly 0 V during startup, which creates a stable operating point of 0 V on the reference output. Because the ADA4084-x is a bipolar amplifier, its negative output swing is limited by the typical output low voltage (V_{OL}) specification of 50 mV, preventing the amplifier output from reaching true ground.

Other than proper startup, most op amps have little to no effect on the ADR1000 reference specification. Op amp parameters such as offset and noise do not significantly affect the performance of the ADR1000 applications circuit. Referring to Figure 9, Q1 runs at a gain of approximately 230, which acts as an additional gain stage in between the Zener reference and the amplifier. This stage effectively attenuates any noise or offset contribution by 230:1.

CHOOSING EXTERNAL RESISTORS

Although the ADR1000 schematic reduces the external resistance sensitivity by a factor of 200 or more, care must be taken in selecting certain components. For example, if a resistor exhibited 200 ppm long-term drift, that affects the reference output by only 1 ppm. In absolute terms, 1 ppm is a small value but significant compared to the relative stability of the ADR1000. Resistors R1, R2, R4, and R5 are metal foil, wire wound, or precision thin film to minimize noise, long-term drift, and temperature coefficient. Table 7 shows the ratio of resistor change to reference voltage change.

Table 7. Application Circuit Resistor Attenuation Factors

Component	Attenuation Factor
R1	340:1
R2	230:1
R3	3900:1 at unheated tempco = 20 ppm/°C (I_Z = 5 mA)
R4, R5	208:1 at unheated tempco = 20 ppm/°C (I_Z = 5 mA)

For example, if R1 has a tempco of 10 ppm/°C, it causes the V_{REF} tempco to vary by 10/340 = 0.03 ppm/°C. Also, if R1 exhibits a long-term drift of 40 ppm, it causes a 40/340 = 0.12 ppm change in reference voltage.

The unheated tempco condition for R3, R4, and R5 is included in Table 7 because those resistors thermostatically control IC temperature. Therefore, the unheated drift of the reference loop is significant. The R4 and R5 tempcos must track to prevent any dependence of the die set temperature on ambient temperature.

APPLICATIONS INFORMATION

BASIC CONNECTION

Figure 9 shows the recommend typical connection diagram for using the ADR1000. In addition, this diagram is the circuit configuration used during the evaluation of the ADR1000. Resistors R4 and R5 are precision resistors.

AVOIDING THERMOCOUPLE ERRORS

Thermocouples are voltage offsets that occur whenever two dissimilar metals form a junction. For example, the TO-99 package leads are made of Kovar® and must be soldered to a copper trace in a PCB design. Kovar copper junctions are known to cause thermocouple errors (thermal electromotive force (EMF)) of 35 µV/°C, which is 50 times the theoretical temperature coefficient of the ADR1000. Thermocouple errors can be avoided by ensuring that critical pins are always at the same temperature. In Figure 9, the reference voltage is sensed between Pin 7 (GND) and Pin 3 (V_{REF}) of the ADR1000. Therefore, ensure that there are no extraneous heat sources to cause a thermal gradient between these two pins. It is also recommended to use air covers over the ADR1000, as well as the temperature set resistors, R4 and R5, to prevent air currents from disturbing these leads. Because the TO-99 package is a through-hole package, even the portion of the leads that protrudes to the underside of the board must be covered for optimal stability over time and temperature. Board cutouts can isolate unwanted heat sources from the ADR1000. Ensure that the temperature set divider resistors, R4 and R5, are wire wound or metal foil to minimize temperature drift and thermocouple errors. Table 8 shows the comparative effect of thermal EMF in component leads, with the attenuation factor calculated for each, and overall reference drift in ppm/°C. Note that the most sensitive component is the ADR1000 itself, due to the Kovar lead to Copper board connection, followed by R5 and R1. The 10 µV/ºC number assumed for the resistor thermocouples is a conservative worst case value. Metal foil resistors have much lower thermal EMF.

Table 8. External Component Thermocouple Attenuation Factors

Component	Attenuation Factor	Sensitivity (µV/°C)	Sensitivity (ppm/°C)
ADR1000 (Kovar-Cu)	35 µV/ºC × 1	35	5.3
R1	10 µV/ºC × 0.033	0.33	0.05
R2	10 µV/ºC × 0.005	0.05	0.008
R3	10 µV/ºC × 0.001	0.01	0.002
R4	10 µV/ºC × 0.01	0.1	0.015
R5	10 µV/ºC × 0.15	1.5	0.23
R8	10 µV/ºC × 0.001	0.01	0.002

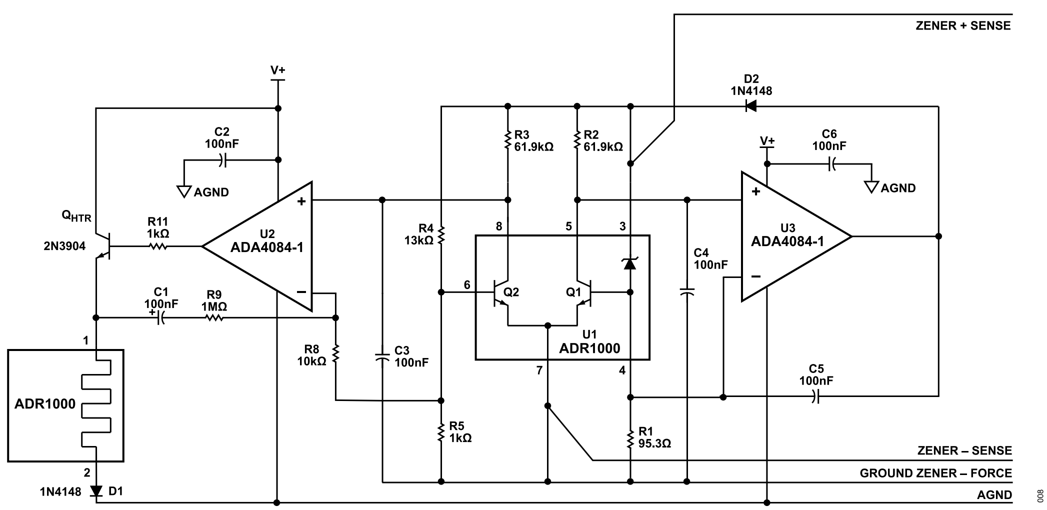


Figure 9. Typical Connection Diagram

OUTLINE DIMENSIONS

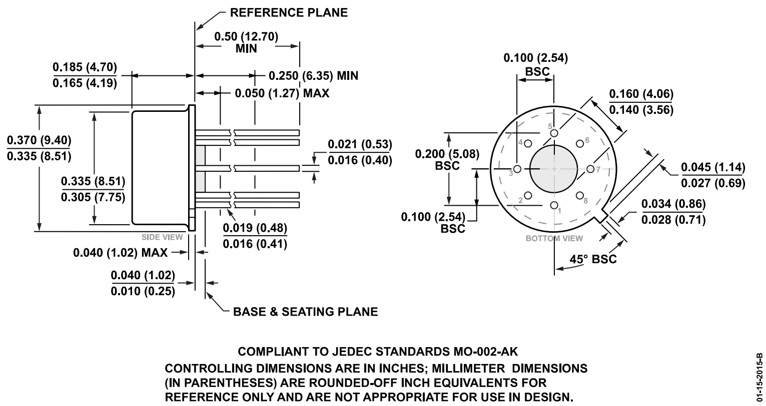


Figure 10. 8-Pin Metal Header
(H-08)
Dimensions shown in inches (millimeters)

Updated: December 17, 2021

ORDERING GUIDE

Model[1]	Temperature Range	Package Description	Package Option
ADR1000AHZ	-40°C to +125°C	ROUND HEADER/METAL CAN	H-08

[1] Z = RoHS Compliant Part.

ANALOG DEVICES

One Analog Way, Wilmington, MA 01887-2356, U.S.A.