AN-225 IC Temperature Sensor Provides Thermocouple Cold-Junction Compensation

ABSTRACT

Two circuits using the LM335 for thermocouple cold-junction compensation have been described. With a single room temperature calibration, these circuits are accurate to ±¾°C over a 0°C to 70°C temperature range using J or K type thermocouples. In addition, a thermocouple amplifier using an LM335 for cold-junction compensation has been described for which worst case error can be as low as 1°C per 40°C change in ambient.

Contents

List of Figures

List of Tables

1   Introduction

Due to their low cost and ease of use, thermocouples are still a popular means for making temperature measurements up to several thousand degrees centigrade. A thermocouple is made by joining wires of two different metals as shown in Figure 1. The output voltage is approximately proportional to the temperature difference between the measuring junction and the reference junction. This constant of proportionality is known as the Seebeck coefficient and ranges from 5 µV/°C to 50 µV/°C for commonly used thermocouples.
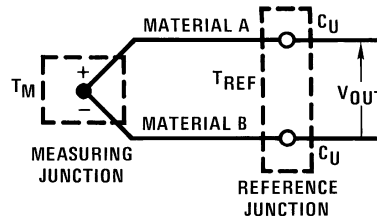
$V_{OUT} \simeq \infty (T_M - T_{REF})$

Figure 1. Thermocouple

Because a thermocouple is sensitive to a temperature *difference*, the temperature at the reference junction must be known in order to make a temperature measurement. One way to do this is to keep the reference junction in an ice bath. This has the advantage of zero output voltage at 0°C, making thermocouple tables usable. A more convenient approach, known as cold-junction compensation, is to add a compensating voltage to the thermocouple output so that the reference junction appears to be at 0°C independent of the actual temperature. If this voltage is made proportional to temperature with the same constant of proportionality as the thermocouple, changes in ambient temperature will have no effect on output voltage.

An IC temperature sensor such as the LM135/LM235/LM335, which has a very linear voltage vs. temperature characteristic, is a natural choice to use in this compensation circuit. The LM135 operates by sensing the difference of base-emitter voltage of two transistors running at different current levels and acts like a zener diode with a breakdown voltage proportional to absolute temperature at 10 mV/°K. Furthermore, because the LM135 extrapolates to zero output at 0°K, the temperature coefficient of the compensation circuit can be adjusted at room temperature without requiring any temperature cycling.

2   Sources of Error

There will be several sources of error involved when measuring temperature with thermocouples. The most basic of these is the tolerance of the thermocouple itself, due to varying composition of the wire material. Note that this tolerance states how much the voltage vs. temperature characteristic differs from that of an ideal thermocouple and has nothing to do with nonlinearity. Tolerance is typically ±¾% of reading for J, K, and T types or ±½% for S and R types, so that a measurement of 1000°C may be off by as much as 7.5°C. Special wire is available with half this error guaranteed.

Additional error can be introduced by the compensation circuitry. For perfect compensation, the compensation circuit must match the output of an ice-point-referenced thermocouple at ambient. It is difficult to match the thermocouple's nonlinear voltage vs. temperature characteristic with a linear absolute temperature sensor, so a "best fit" linear approximation must be made. In Figure 2 this nonlinearity is plotted as a function of temperature for several thermocouple types. The K type is the most linear, while the S type is one of the least linear. When using an absolute temperature sensor for cold-junction compensation, compensation error is a function of both thermocouple nonlinearity and also the variation in ambient temperature, since the straight-line approximation to the thermocouple characteristic is more valid for small deviations.
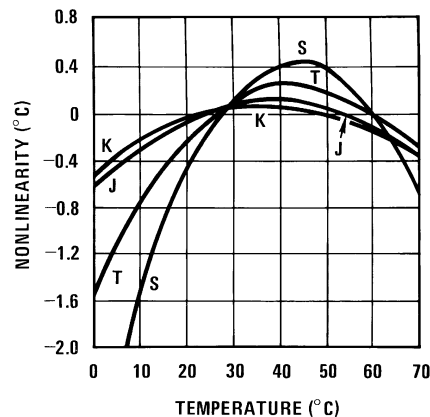
Figure 2. Thermocouple Nonlinearity

Of course, increased error results if, due to component inaccuracies, the compensation circuit does not produce the ideal output. The LM335 is very linear with respect to absolute temperature and introduces little error. However, the complete circuit must contain resistors and a voltage reference in order to obtain the proper offset and scaling. Initial tolerances can be trimmed out, but the temperature coefficient of these external components is usually the limiting factor (unless this drift is measured and trimmed out).

3   Circuit Description

A single-supply circuit is shown in Figure 3. R3 and R4 divide down the 10 mV/°K output of the LM335 to match the Seebeck coefficient of the thermocouple. The LM329B and its associated voltage divider provide a voltage to buck out the 0°C output of the LM335. To calibrate, adjust R1 so that V1 = <5°C T, where <5°C is the Seebeck coefficient and T is the ambient temperature in degrees *Kelvin*. Then, adjust R2 so that V1−V2 is equal to the thermocouple output voltage at the known ambient temperature.

To achieve maximum performance from this circuit the resistors must be carefully chosen. R3 through R6 should be precision wirewounds, Vishay bulk metal or precision metal film types with a 1% tolerance and a temperature coefficient of ±5 ppm/°C or better. In addition to having a low TCR, these resistors exhibit low thermal emf when the leads are at different temperatures, ranging from 3 µV/°C for the TRW MAR to only 0.3 µV/°C for the Vishay types. This is especially important when using S or R type thermocouples that output only 6 µV/°C. R7 should have a temperature coefficient of ±25 ppm/°C or better and a 1% tolerance. Note that the potentiometers are placed where their absolute resistance is not important so that their TCR is not critical. However, the trim pots should be of a stable cermet type. While multi-turn pots are usually considered to have the best resolution, many modern single-turn pots are just as easy to set to within ±0.1% of the desired value as the multi-turn pots.

Also single-turn pots usually have superior stability of setting, versus shock or vibration. Thus, good single-turn cermet pots (such as Allen Bradley type E, Weston series 840, or CTS series 360) should be considered as good candidates for high-resolution trim applications, competing with the more obvious (but slightly more expensive) multi-turn trim pots such as Allen Bradley type RT or MT, Weston type 850, or similar.

With a room temperature adjustment, drift error will be only ±½°C at 70°C and ±¼°C at 0°C. Thermocouple nonlinearity results in additional compensation error. The chromel/alumel (type K) thermocouple is the most linear. With this type, a compensation accuracy of ±¾°C can be obtained over a 0°C–70°C range. Performance with an iron-constantan thermocouple is almost as good. To keep the error small for the less linear S and T type thermocouples, the ambient temperature must be kept within a more limited range, such as 15°C to 50°C. Of course, more accurate compensation over a narrower temperature range can be obtained with any thermocouple type by the proper adjustment of voltage TC and offset.

Standard metal-film resistors cost substantially less than precision types and may be substituted with a reduction in accuracy or temperature range. Using 50 ppm/°C resistors, the circuit can achieve ½°C error over a 10°C range. Switching to 25 ppm resistors will halve this error. Tin oxide resistors should be avoided since they generate a thermal emf of 20 µV for 1°C temperature difference in lead temperature as opposed to 2 µV/°C for nichrome or 4.3 µV/°C for cermet types. Resistor networks exhibit good tracking, with 50 ppm/°C obtainable for thick film and 5 ppm/°C for thin film. In order to obtain the large resistor ratios needed, one can use series and parallel connections of resistors on one or more substrates.
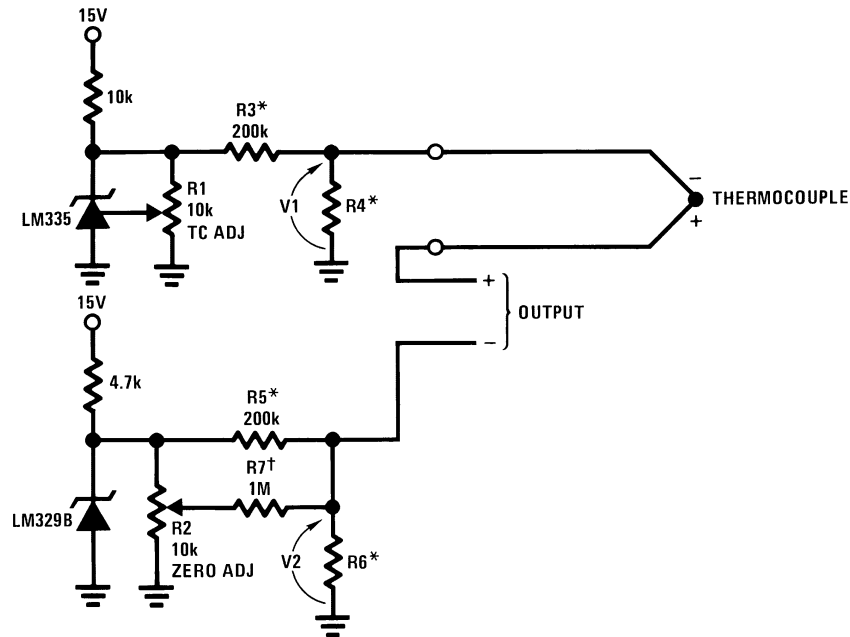[1]

Figure 3. Thermocouple Cold-Junction Compensation Using Single Power Supply

[1]   See Appendix A for calculation of Seebeck coefficient.

Thermocouple	Seebeck	R4	R6
Type	Coefficient	(Ω)	(Ω)
	(µV/°C)		
J	52.3	1050	385
T	42.8	856	315
K	40.8	816	300
S	6.4	128	46.3

$$\text{choose } R4 = \frac{\alpha}{10 \text{ mV/°C}} \bullet R3$$

$$\text{choose } R6 = \frac{-T_o \bullet \alpha}{V_Z} \bullet (0.9R5)$$

$$\text{choose } R7 = 5 \bullet R5$$

where T_o is absolute zero (-273.16°C)

[1][2] V_Z is the reference voltage (6.95V for LM329B)

A circuit for use with grounded thermocouples is shown in Figure 4. If dual supplies are available, this circuit is preferable to that of Figure 3 since it achieves similar performance with fewer low TC resistors. To trim, short out the LM329B and adjust R5 so that $V_o = <5$°C T, where <5°C is the Seebeck coefficient of the thermocouple and T is the absolute temperature. Remove the short and adjust R4 so that V_o equals the thermocouple output voltage at ambient. A good grounding system is essential here, for any ground differential will appear in series with the thermocouple output.

[1]   *R3 thru R6 are 1%, 5 ppm/°C. (10 ppm/°C tracking.)
[2]   †R7 is 1%, 25 ppm/°C.

An electronic thermometer with a 10 mV/°C output from 0°C to 1300°C is seen in Figure 5. The trimming procedure is as follows: first short out the LM329B, the LM335 and the thermocouple. Measure the output voltage (equal to the input offset voltage times the voltage gain). Then apply a 50 mV input voltage and adjust the GAIN ADJUST pot until the output voltage is 12.25V above the previously measured value. Next, short out the thermocouple again and remove the short across the LM335. Adjust the TC ADJUST pot so that the output voltage equals 10 mV/°K times the absolute temperature. Finally, remove the short across the LM329B and adjust the ZERO ADJUST pot so that the output voltage equals 10 mV/°C times the ambient temperature in °C.
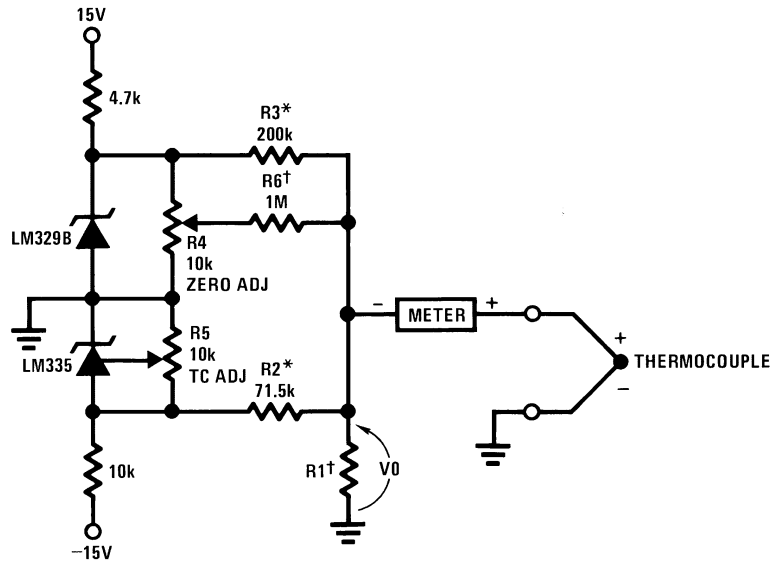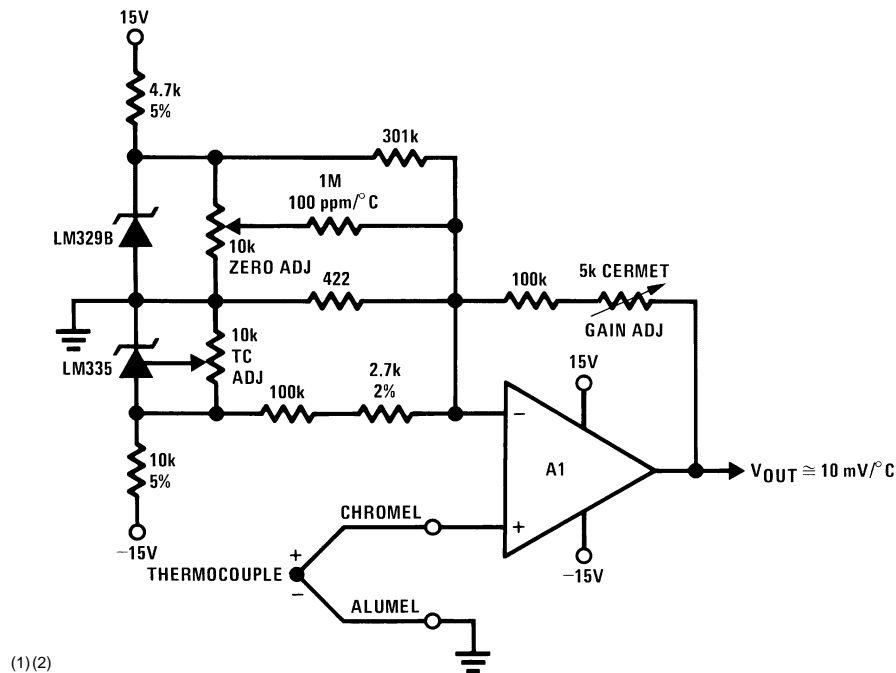

Figure 4. Cold-Junction Compensation for Grounded Thermocouple

Thermocouple	R1	Seebeck
Type	(Ω)	Coefficient
		(µV/°C)
J	377	52.3
T	308	42.8
K	293	40.8
S	45.8	6.4

All fixed resistors ±1%, 25 ppm/°C unless otherwise indicated.
A1 should be a low drift type such as LM308A or LH0044C. See text.

Figure 5. Centigrade Thermometer with Cold-Junction Compensation

The error over a 0°C to 1300°C range due to thermocouple nonlinearity is only 2.5% maximum. Table 1 shows the error due to thermocouple nonlinearity as a function of temperature. This error is under 1°C for 0°C to 300°C but is as high as 17°C over the entire range. This may be corrected with a nonlinear shaping network. If the output is digitized, correction factors can be stored in a ROM and added in via hardware or software.

The major cause of temperature drift will be the input offset voltage drift of the op amp. The LM308A has a specified maximum offset voltage drift of 5 µV/°C which will result in a 1°C error for every 8°C change in ambient. Substitution of an LH0044C with its 1 µV/°C maximum offset voltage drift will reduce this error to 1°C per 40°C. If desired, this temperature drift can be trimmed out with only one temperature cycle by following the procedure detailed in Appendix B.

4   Construction Hints

The LM335 must be held isothermal with the thermocouple reference junction for proper compensation. Either of the techniques of Figure 6 or Figure 7 may be used.

Hermetic ICs use Kovar leads which output 35 µV/°C referenced to copper. In the circuit of Figure 5, the low level thermocouple output is connected directly to the op amp input. To avoid this from causing a problem, both input leads of the op amp must be maintained at the same temperature. This is easily achieved by terminating both leads to identically sized copper pads and keeping them away from thermal gradients caused by components that generate significant heat.

---

[1]   *R2 and R3 are 1%, 10 ppm/°C. (20 ppm/°C tracking.)
[2]   †R1 and R6 are 1%, 50 ppm/°C.
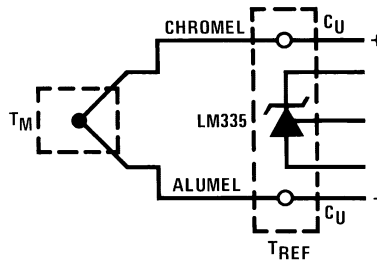
Figure 6. (a) Methods for Sensing Temperature of Reference Junction
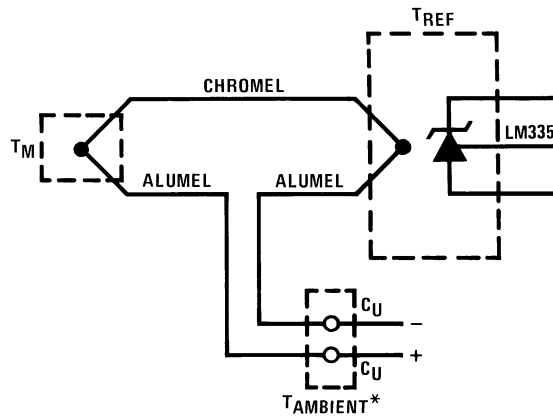
*Has no effect on measurement.

Figure 7. (b) Methods for Sensing Temperature of Reference Junction

Table 1. Nonlinearity Error of Thermometer Using Type K Thermocouple (Scale Factor 25.47°C/μV)

°C	Error (°C)	°C	Error (°C)
10	−0.3	200	−0.1
20	−0.4	210	−0.2
30	−0.4	220	−0.4
40	−0.4	240	−0.6
50	−0.3	260	−0.5
60	−0.2	280	−0.4
70	0	300	−0.1
80	0.2	350	1.2
90	0.4	400	2.8
100	0.6	500	7.1
110	0.8	600	11.8
120	0.9	700	15.7
130	0.9	800	17.6
140	0.9	900	17.1
150	0.8	1000	14.0
160	0.7	1100	8.3
170	0.5	1200	−0.3
180	0.3	1300	−13
190	0.1		

Before trimming, all components should be stabilized. A 24-hour bake at 85°C is usually sufficient. Care should be taken when trimming to maintain the temperature of the LM335 constant, as body heat nearby can introduce significant errors. One should either keep the circuit in moving air or house it in a box, leaving holes for the trimpots.

5   Appendix A Determination of Seebeck Coefficient

Because of the nonlinear relation of output voltage vs. temperature for a thermocouple, there is no unique value of its Seebeck coefficient <5°C. Instead, one must approximate the thermocouple function with a straight line and determine <5°C from the line's slope for the temperature range of interest. On a graph, the error of the line approximation is easily visible as the vertical distance between the line and the nonlinear function. Thermocouple nonlinearity is not so gross, so that a numerical error calculation is better than the graphical approach.

Most thermocouple functions have positive curvature, so that a linear approximation with minimum mean-square error will intersect the function at two points. As a first cut, one can pick these points at the ⅓ and ⅔ points across the ambient temperature range. Then calculate the difference between the linear approximation and the thermocouple. This error will usually then be a maximum at the midpoint and endpoints of the temperature range. If the error becomes too large at either temperature extreme, one can modify the slope or the intercept of the line. Once the linear approximation is found that minimizes error over the temperature range, use its slope as the Seebeck coefficient value when designing a cold-junction compensator.

An example of this procedure for a type S thermocouple is shown in Table 2. Note that picking the two intercepts (zero error points) close together results in less error over a narrower temperature range.

[1] A collection of thermocouple tables useful for this purpose is found in the Omega Temperature Measurement Handbook published by Omega Engineering, Stamford, Connecticut.

Table 2. Linear Approximations to Type S Thermocouple

Centigrade Temperature	Type S Thermocouple Output (µV)	Approximation #1 Zero Error at 25°C and 60°C			Approximation #2 Zero Error at 30°C and 50°C		
		Linear Approx.	Error [1] µV	°C	Linear Approx.	Error [1] µV	°C
0°	0	−17	−17	−2.7°	−16	−16	−2.8°
5°	27	15	−12	−1.9°	16	−11	−1.7°
10°	55	46	−9	−1.4°	47	−8	−1.3°
15°	84	78	−6	−0.9°	78	−6	−0.9°
20°	113	110	−3	−0.5°	110	−3	−0.5°
25°	142	142	0	0	142	−1	−0.2°
30°	173	174	1	0.2°	173	0	0
35°	203	206	3	0.5°	204	1	0.2°
40°	235	238	3	0.5°	236	1	0.2°
45°	266	270	4	0.6°	268	2	0.3°
50°	299	301	2	0.3°	299	0	0
55°	331	333	2	0.3°	330	−1	−0.2°
60°	365	365	0	0	362	−3	−0.5°
65°	398	397	−1	−0.2°	394	−4	−0.6°
70°	432	429	−3	−0.5°	425	−7	−1.1°
		<5°C = 6.4 µV/°C 0.6°C error for 20°C < T < 70°C			<5°C = 6.3 µV/°C 0.3°C error for 25°C < T < 50°C		

[1] Error is the difference between linear approximation and actual thermocouple output in µV. To convert error to °C, divide by Seebeck coefficient.

6   Appendix B Technique for Trimming Out Offset Drift

Short out the thermocouple input and measure the circuit output voltage at 25°C and at 70°C. Calculate the output voltage temperature coefficient, β as shown.

$$\beta = \frac{V_{OUT\,(70°C)} - V_{OUT(25°C)}}{45°K} \text{ in mV/°K}$$

(1)

Next, short out the LM329B and adjust the TC ADJ pot so that V_{OUT} = (20 mV/°K − β) × 298°K at 25°C. Now remove the short across the LM329B and adjust the ZERO ADJUST pot so that V_{OUT} = 246 mV at 25°C (246 times the 25°C output of an ice-point-referenced thermocouple).

This procedure compensates for all sources of drift, including resistor TC, reference drift (±20 ppm/°C maximum for the LM329B) and op amp offset drift. Performance will be limited only by TC nonlinearities and measurement accuracy.

7   References

LB-22 Low Drift Amplifiers (SNOA728)

AN-222 *Super Matched Bipolar Transistor Pair Sets New Standards for Drift and Noise* (SNOA626)

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have *not* been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		Applications	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2013, Texas Instruments Incorporated