Project 2: “On-chip” Real-time Polymerase Chain Reaction – Week 2 Thermocycling

BE/EE189 Design and Construction of Biodevices

Spring 2017

Instructions

Only one lab report is required of each group. Document clearly how your circuit and VI work

- Include your VI in your submission along with discussion of design considerations.
- Comment on the question embedded in Task 3 on page .
- Emphasis is placed on the analysis and demonstration of understanding of the functionality, performance, and limitations of the system.

Introduction

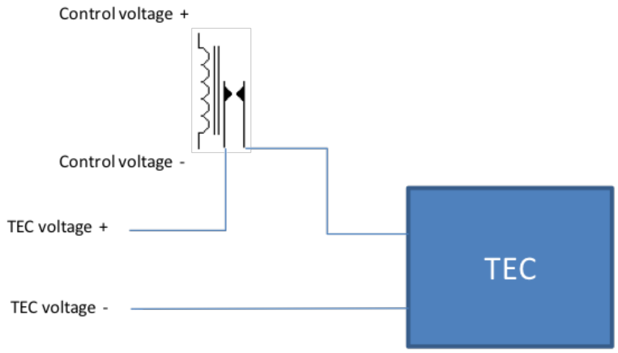
The thermocycler design consists of three different subsystems: heating, cooling, and sensing. During the heating process, the heating subsystem is turned on until the temperature reaches the desired value, as detected by the sensing subsystem. For maintaining some fixed temperature, the heating subsystem is turned on and off as controlled by the feedback from the sensing system. For fast cooling, the cooling subsystem will be turned on until the temperature reaches the desired value. The following sections will describe the details of the subsystems.

Subsystems

Heating

A thermoelectric cooler (TEC) is the central part in the subsystem. A TEC uses the Peltier effect to work as a solid state heat pump. It ideally absorbs heat through one side (thus making that side cool) and releases it on the other side (thus making that side hot), creating a temperature differential. The direction it pumps heat is dependent on the direction of the current flowing through it.

For purely heating applications, a 12 V DC power supply is used to drive the TEC, and the on and off can be controlled by a 5 V signal through the use of a relay. The following is the diagram for such a subsystem.



Cooling

When the heating subsystem is turned off, the TEC will cool down to room temperature naturally. But we can cool the system quicker by drawing away heat from the surface using a heatsink and fan. However, even this process can be too slow for a biological application.

Dual Active Heating and Cooling

A more effective heating and cooling system must incorporate heat sinks and sources creatively and utilize the fact that the TEC can both heat and cool based on the direction of the current flow.

Picture a TEC that is not directly connected to a fan or heatsink (i.e. - the TEC is suspended in air). As usual, when current flows through the device, the TEC creates a temperature differential. At some point, there is no more heat (locally) to absorb from the cold side, and the hot side (locally) cannot transfer the heat fast enough to the air. Eventually, the device can overheat in this situation and fail.

Now imagine that a TEC has a heat sink attached to both sides. Imagine that each sink has a fan that aids in convective heat transfer between the heatsink and the surrounding air. The figure below is a visual example of this. We will refer to the bottom side of the TEC as side A, and the top side as side B. Imagine current is flowing in one direction through the TEC, which pumps heat from side A to side B. The heat "sink" on side A will now act more like a heat "source". Convective heat transfer from the surrounding air into the heat sink on that side will provide an ideal supply of heat that can be pumped to side B. Meanwhile, the heat sink on side B will act like a true "sink" and draw the heat away from side B and dump it into the air. This prevents side B from overheating and keeps the temperature gradient across the TEC stable. When the current direction is reversed, this whole process is repeated, only in the opposite direction. This time, heat is pumped from side B to side A, where the heatsink on side B acts as a source and the heatsink on side A draws the heat away from the TEC.

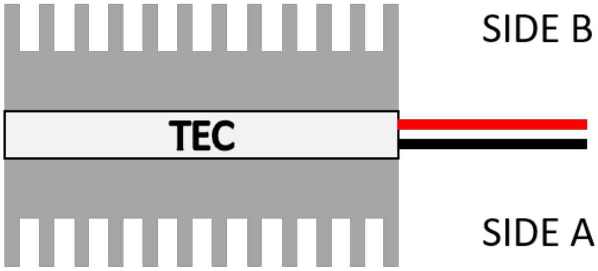


Figure 1: TEC with heat sinks on both sides

Now try to imagine this scenario for the purposes of this lab. Instead of a heat sink on side B, picture a sample holder on that side. When current flows in one direction through the TEC, the sample holder draws away heat from side B. Since the sample holder does not transfer the heat to the air all that well, the heat is directed towards the sample and is heated. When current flows in the opposite direction through the TEC, the sample holder is now supplying side B with heat to pump across to side A. Again, this heat is drawn from the sample, and thus, cools the sample down.

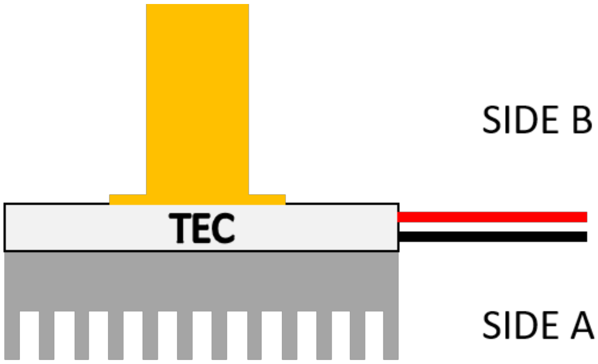
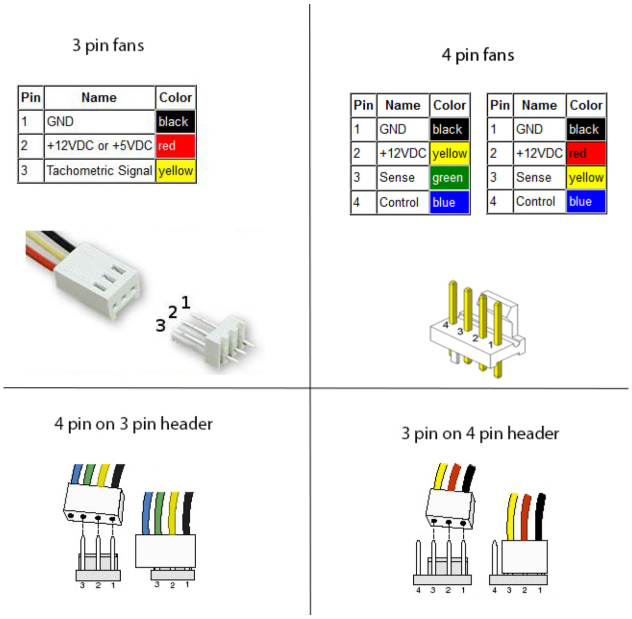


Figure 2: TEC with heat sink on one side and sample holder on other

You will be implementing exactly the figure above for this lab. Each of you will receive a fan/heatsink cooler, a TEC, and sample holder. The fan/heatsink cooler must ALWAYS be powered on when the TEC is in use. You can refer to the 4 pin pinout below. To supply the 12 V for the fan, use the variable power supply function on the ELVIS Board instrument launcher.



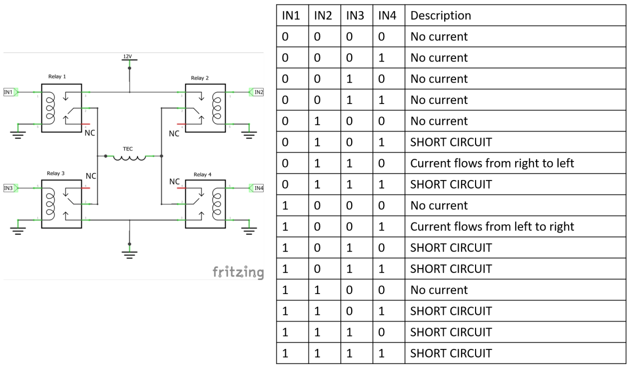
Pin	Name	Color
1	GND	black
2	+12VDC or +5VDC	red
3	Tachometric Signal	yellow

Pin	Name	Color
1	GND	black
2	+12VDC	yellow
3	Sense	green
4	Control	blue

Pin	Name	Color
1	GND	black
2	+12VDC	red
3	Sense	yellow
4	Control	blue

Figure 3: Pinout for 3 and 4 pin fans

When you are ready, you will be given thermal paste to bond the TEC to the cooler, and then the TEC to the sample holder. There are several ways you can control the current going through the TEC. One example given below is an H-bridge circuit that has been implemented using the 4 relay modules each of you contain. You will use a separate power supply to power the TEC with 25 V. The relay module can be powered directly from the ELVIS board 5 V and ground line, and the input signals on the relay can be supplied by the DIO pins.

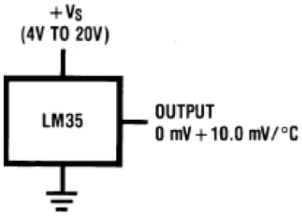


IN1	IN2	IN3	IN4	Description
0	0	0	0	No current
0	0	0	1	No current
0	0	1	0	No current
0	0	1	1	No current
0	1	0	0	No current
0	1	0	1	SHORT CIRCUIT
0	1	1	0	Current flows from right to left
0	1	1	1	SHORT CIRCUIT
1	0	0	0	No current
1	0	0	1	Current flows from left to right
1	0	1	0	SHORT CIRCUIT
1	0	1	1	SHORT CIRCUIT
1	1	0	0	No current
1	1	0	1	SHORT CIRCUIT
1	1	1	0	SHORT CIRCUIT
1	1	1	1	SHORT CIRCUIT

Figure 4: Example H-Bridge setup using relay module

Sensing

We will use the temperature sensor LM35 for measuring the temperature. Please refer to its data sheet for detailed information. In the experiment, the LM35 is attached to the surface of the sample holder for temperature measurement. You can use the basic diagram as shown below:



The LM35 thermistor is configured this way. The 1st pin can be connected to either 5 or 15 V for power (in fact, it can flexibly take 4 V to 30 V as input.) Pin 3 should be connected to ground. Pin 2 provide a voltage output that scales as 0.01 V/°C. You should calibrate the voltage readings from the LM35 with the actual temperature values measured with a thermometer for accurate temperature reading in your setup. You may need to use a linear fit, temperature point by temperature point correlation with the measured voltage, etc.

Tasks

1. Design and build the heating, cooling and sensing components of the thermocycler.
2. Build a LabVIEW VI that will allow you to control the system. Remember the system has to be able to run the following heating/cooling cycles:

Temperature (°C)	Time	Action
94	2 min	Initial denaturation of DNA
94	30 sec	Denaturation
52	30 sec	Annealing of probe to DNA template strand
72	1 min	Extension
Repeat preceding 3 steps for specified number of cycles		
10	∞	Final cool down and hold until user stops program

   Times, temperatures, and number of cycles should be user controllable. Your system should be able to heat and cool at a rate of ≈1 °C/ sec to 2 °C/ sec. Include as much of the front panel features of the commercial PCR you observed in class as possible.

3. Check that your system is functional. What is the accuracy of the thermistor at the 3 typical temperature set points? Use the probe thermometer to check the temperature of a small amount of water (≈0.1 mL) in a PCR tube. (You can drill a small hole on the tube cover to put the probe in the tube. Be aware that the water might boil and evaporate during the experiment.)

LM35 Precision Centigrade Temperature Sensors

1 Features

- Calibrated Directly in Celsius (Centigrade)
- Linear + 10-mV/°C Scale Factor
- 0.5°C Ensured Accuracy (at 25°C)
- Rated for Full −55°C to 150°C Range
- Suitable for Remote Applications
- Low-Cost Due to Wafer-Level Trimming
- Operates from 4 V to 30 V
- Less than 60-μA Current Drain
- Low Self-Heating, 0.08°C in Still Air
- Non-Linearity Only ±¼°C Typical
- Low-Impedance Output, 0.1 Ω for 1-mA Load

2 Applications

- Power Supplies
- Battery Management
- HVAC
- Appliances

3 Description

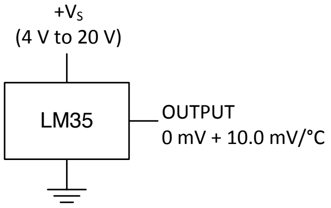
The LM35 series are precision integrated-circuit temperature devices with an output voltage linearly-proportional to the Centigrade temperature. The LM35 device has an advantage over linear temperature sensors calibrated in Kelvin, as the user is not required to subtract a large constant voltage from the output to obtain convenient Centigrade scaling. The LM35 device does not require any external calibration or trimming to provide typical accuracies of ±¼°C at room temperature and ±¾°C over a full −55°C to 150°C temperature range. Lower cost is assured by trimming and calibration at the wafer level. The low-output impedance, linear output, and precise inherent calibration of the LM35 device makes interfacing to readout or control circuitry especially easy. The device is used with single power supplies, or with plus and minus supplies. As the LM35 device draws only 60 μA from the supply, it has very low self-heating of less than 0.1°C in still air. The LM35 device is rated to operate over a −55°C to 150°C temperature range, while the LM35C device is rated for a −40°C to 110°C range (−10° with improved accuracy). The LM35-series devices are available packaged in hermetic TO transistor packages, while the LM35C, LM35CA, and LM35D devices are available in the plastic TO-92 transistor package. The LM35D device is available in an 8-lead surface-mount small-outline package and a plastic TO-220 package.

Device Information[1]

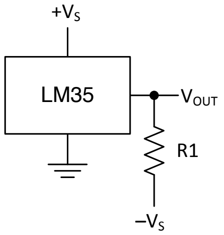
PART NUMBER	PACKAGE	BODY SIZE (NOM)
LM35	TO-CAN (3)	4.699 mm × 4.699 mm
	TO-92 (3)	4.30 mm × 4.30 mm
	SOIC (8)	4.90 mm × 3.91 mm
	TO-220 (3)	14.986 mm × 10.16 mm

(1) For all available packages, see the orderable addendum at the end of the datasheet.

Basic Centigrade Temperature Sensor (2°C to 150°C)



Full-Range Centigrade Temperature Sensor



Choose $R_1 = –V_S / 50\ \mu A$
V_{OUT} = 1500 mV at 150°C
V_{OUT} = 250 mV at 25°C
V_{OUT} = –550 mV at –55°C

Table of Contents

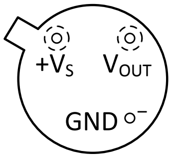
4 Revision History

Changes from Revision D (October 2013) to Revision E	Page
• Added *Pin Configuration and Functions* section, *ESD Ratings* table, *Feature Description* section, *Device Functional Modes*, *Application and Implementation* section, *Power Supply Recommendations* section, *Layout* section, *Device and Documentation Support* section, and *Mechanical, Packaging, and Orderable Information* section	1

Changes from Revision C (July 2013) to Revision D	Page
• Changed *W* to *Ω*	1
• Changed *W* to *Ω* in *Abs Max* tablenote.	4

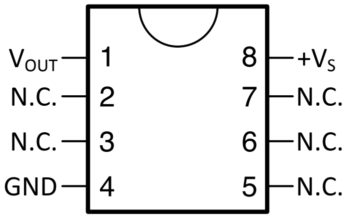
5 Pin Configuration and Functions

NDV Package
3-Pin TO-CAN
(Top View)



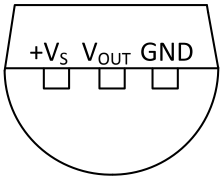
Case is connected to negative pin (GND)

D Package
8-PIN SOIC
(Top View)

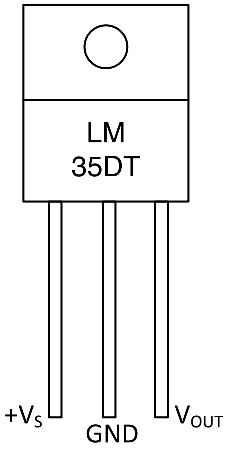


N.C. = No connection

LP Package
3-Pin TO-92
(Bottom View)



NEB Package
3-Pin TO-220
(Top View)



Tab is connected to the negative pin (GND).

NOTE: The LM35DT pinout is different than the discontinued LM35DP

Pin Functions

PIN					TYPE	DESCRIPTION
NAME	TO46	TO92	TO220	SO8		
V_{OUT}	—	—	—	1	O	Temperature Sensor Analog Output
N.C.	—	—	—	2	—	No Connection
	—	—	—	3		
GND	—	—	—	4	GROUND	Device ground pin, connect to power supply negative terminal
N.C.	—	—	—	5	—	No Connection
	—	—	—	6		
	—	—	—	7		
$+V_S$	—	—	—	8	POWER	Positive power supply pin

6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)(2)

		MIN	MAX	UNIT
Supply voltage		–0.2	35	V
Output voltage		–1	6	V
Output current			10	mA
Maximum Junction Temperature, $T_J$max			150	°C
Storage Temperature, T_{stg}	TO-CAN, TO-92 Package	–60	150	°C
	TO-220, SOIC Package	–65	150	

(1) If Military/Aerospace specified devices are required, please contact the Texas Instruments Sales Office/ Distributors for availability and specifications.

(2) Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. DC and AC electrical specifications do not apply when operating the device beyond its rated operating conditions.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001 (1)	±2500	V

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	MAX	UNIT
Specified operating temperature: T_{MIN} to T_{MAX}	LM35, LM35A	–55	150	°C
	LM35C, LM35CA	–40	110	
	LM35D	0	100	
Supply Voltage ($+V_S$)		4	30	V

6.4 Thermal Information

THERMAL METRIC (1)(2)		LM35				UNIT
		NDV	LP	D	NEB	
		3 PINS		8 PINS	3 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	400	180	220	90	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	24	—	—	—	

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.

(2) For additional thermal resistance information, see *Typical Application*.

6.5 Electrical Characteristics: LM35A, LM35CA Limits

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 μA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS	LM35A			LM35CA			UNIT
		TYP	TESTED LIMIT(1)	DESIGN LIMIT(2)	TYP	TESTED LIMIT(1)	DESIGN LIMIT(2)	
Accuracy(3)	T_A = 25°C	±0.2	±0.5		±0.2	±0.5		°C
	T_A = –10°C	±0.3			±0.3		±1	
	$T_A = T_{MAX}$	±0.4	±1		±0.4	±1		
	$T_A = T_{MIN}$	±0.4	±1		±0.4		±1.5	
Nonlinearity(4)	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C	±0.18		±0.35	±0.15		±0.3	°C
Sensor gain (average slope)	$T_{MIN} \le T_A \le T_{MAX}$	10	9.9		10		9.9	mV/°C
	–40°C ≤ T_J ≤ 125°C	10	10.1		10		10.1	
Load regulation(5) 0 ≤ I_L ≤ 1 mA	T_A = 25°C	±0.4	±1		±0.4	±1		mV/mA
	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C	±0.5		±3	±0.5		±3	
Line regulation(5)	T_A = 25°C	±0.01	±0.05		±0.01	±0.05		mV/V
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C	±0.02		±0.1	±0.02		±0.1	
Quiescent current(6)	V_S = 5 V, 25°C	56	67		56	67		μA
	V_S = 5 V, –40°C ≤ T_J ≤ 125°C	105		131	91		114	
	V_S = 30 V, 25°C	56.2	68		56.2	68		
	V_S = 30 V, –40°C ≤ T_J ≤ 125°C	105.5		133	91.5		116	
Change of quiescent current(5)	4 V ≤ V_S ≤ 30 V, 25°C	0.2	1		0.2	1		μA
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C	0.5		2	0.5		2	
Temperature coefficient of quiescent current	–40°C ≤ T_J ≤ 125°C	0.39		0.5	0.39		0.5	μA/°C
Minimum temperature for rate accuracy	In circuit of Figure 14, I_L = 0	1.5		2	1.5		2	°C
Long term stability	$T_J = T_{MAX}$, for 1000 hours	±0.08			±0.08			°C

(1) Tested Limits are ensured and 100% tested in production.

(2) Design Limits are ensured (but not 100% production tested) over the indicated temperature and supply voltage ranges. These limits are not used to calculate outgoing quality levels.

(3) Accuracy is defined as the error between the output voltage and 10 mv/°C times the case temperature of the device, at specified conditions of voltage, current, and temperature (expressed in °C).

(4) Non-linearity is defined as the deviation of the output-voltage-versus-temperature curve from the best-fit straight line, over the rated temperature range of the device.

(5) Regulation is measured at constant junction temperature, using pulse testing with a low duty cycle. Changes in output due to heating effects can be computed by multiplying the internal dissipation by the thermal resistance.

(6) Quiescent current is defined in the circuit of Figure 14.

6.6 Electrical Characteristics: LM35A, LM35CA

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 µA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS		LM35A			LM35CA			UNIT
			MIN	TYP	MAX	TYP	TYP	MAX	
Accuracy(1)	T_A = 25°C			±0.2			±0.2		°C
		Tested Limit(2)			±0.5			±0.5	
		Design Limit(3)							
	T_A = –10°C			±0.3			±0.3		
		Tested Limit(2)							
		Design Limit(3)						±1	
	$T_A = T_{MAX}$			±0.4			±0.4		
		Tested Limit(2)			±1			±1	
		Design Limit(3)							
	$T_A = T_{MIN}$			±0.4			±0.4		
		Tested Limit(2)			±1				
		Design Limit(3)						±1.5	
Nonlinearity(4)	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C			±0.18			±0.15		°C
		Tested Limit(2)							
		Design Limit(3)			±0.35			±0.3	
Sensor gain (average slope)	$T_{MIN} \le T_A \le T_{MAX}$			10			10		mV/°C
		Tested Limit(2)			9.9				
		Design Limit(3)						9.9	
	–40°C ≤ T_J ≤ 125°C			10			10		
		Tested Limit(2)			10.1				
		Design Limit(3)						10.1	
Load regulation(5) 0 ≤ I_L ≤ 1 mA	T_A = 25°C			±0.4			±0.4		mV/mA
		Tested Limit(2)			±1			±1	
		Design Limit(3)							
	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C			±0.5			±0.5		
		Tested Limit(2)							
		Design Limit(3)			±3			±3	
Line regulation(5)	T_A = 25°C			±0.01			±0.01		mV/V
		Tested Limit(2)			±0.05			±0.05	
		Design Limit(3)							
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C			±0.02			±0.02		
		Tested Limit(2)							
		Design Limit(3)			±0.1			±0.1	

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(1) Accuracy is defined as the error between the output voltage and 10 mv/°C times the case temperature of the device, at specified conditions of voltage, current, and temperature (expressed in °C).

(2) Tested Limits are ensured and 100% tested in production.

(3) Design Limits are ensured (but not 100% production tested) over the indicated temperature and supply voltage ranges. These limits are not used to calculate outgoing quality levels.

(4) Non-linearity is defined as the deviation of the output-voltage-versus-temperature curve from the best-fit straight line, over the rated temperature range of the device.

(5) Regulation is measured at constant junction temperature, using pulse testing with a low duty cycle. Changes in output due to heating effects can be computed by multiplying the internal dissipation by the thermal resistance.

Electrical Characteristics: LM35A, LM35CA (continued)

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 µA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS		LM35A			LM35CA			UNIT
			MIN	TYP	MAX	TYP	TYP	MAX	
Quiescent current(6)	V_S = 5 V, 25°C			56			56		µA
		Tested Limit(2)			67			67	
		Design Limit(3)							
	V_S = 5 V, –40°C ≤ T_J ≤ 125°C			105			91		
		Tested Limit(2)							
		Design Limit(3)			131			114	
	V_S = 30 V, 25°C			56.2			56.2		
		Tested Limit(2)			68			68	
		Design Limit(3)							
	V_S = 30 V, –40°C ≤ T_J ≤ 125°C			105.5			91.5		
		Tested Limit(2)							
		Design Limit(3)			133			116	
Change of quiescent current(5)	4 V ≤ V_S ≤ 30 V, 25°C			0.2			0.2		µA
		Tested Limit(2)			1			1	
		Design Limit(3)							
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C			0.5			0.5		
		Tested Limit(2)							
		Design Limit(3)			2			2	
Temperature coefficient of quiescent current	–40°C ≤ T_J ≤ 125°C			0.39			0.39		µA/°C
		Tested Limit(2)							
		Design Limit(3)			0.5			0.5	
Minimum temperature for rate accuracy	In circuit of Figure 14, I_L = 0			1.5			1.5		°C
		Tested Limit(2)							
		Design Limit(3)			2			2	
Long term stability	T_J = T_{MAX}, for 1000 hours			±0.08			±0.08		°C

(6) Quiescent current is defined in the circuit of Figure 14.

6.7 Electrical Characteristics: LM35, LM35C, LM35D Limits

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 μA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS	LM35			LM35C, LM35D			UNIT
		TYP	TESTED LIMIT[1]	DESIGN LIMIT[2]	TYP	TESTED LIMIT[1]	DESIGN LIMIT[2]	
Accuracy, LM35, LM35C[3]	T_A = 25°C	±0.4	±1		±0.4	±1		°C
	T_A = –10°C	±0.5			±0.5		±1.5	
	$T_A = T_{MAX}$	±0.8	±1.5		±0.8		±1.5	
	$T_A = T_{MIN}$	±0.8		±1.5	±0.8		±2	
Accuracy, LM35D[3]	T_A = 25°C				±0.6	±1.5		°C
	$T_A = T_{MAX}$				±0.9		±2	
	$T_A = T_{MIN}$				±0.9		±2	
Nonlinearity[4]	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C	±0.3		±0.5	±0.2		±0.5	°C
Sensor gain (average slope)	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C	10	9.8		10		9.8	mV/°C
		10	10.2		10		10.2	
Load regulation[5] 0 ≤ I_L ≤ 1 mA	T_A = 25°C	±0.4	±2		±0.4	±2		mV/mA
	$T_{MIN} \le T_A \le T_{MAX}$, –40°C ≤ T_J ≤ 125°C	±0.5		±5	±0.5		±5	
Line regulation[5]	T_A = 25°C	±0.01	±0.1		±0.01	±0.1		mV/V
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C	±0.02		±0.2	±0.02		±0.2	
Quiescent current[6]	V_S = 5 V, 25°C	56	80		56	80		μA
	V_S = 5 V, –40°C ≤ T_J ≤ 125°C	105		158	91		138	
	V_S = 30 V, 25°C	56.2	82		56.2	82		
	V_S = 30 V, –40°C ≤ T_J ≤ 125°C	105.5		161	91.5		141	
Change of quiescent current[5]	4 V ≤ V_S ≤ 30 V, 25°C	0.2	2		0.2	2		μA
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C	0.5		3	0.5		**3**	
Temperature coefficient of quiescent current	–40°C ≤ T_J ≤ 125°C	0.39		0.7	0.39		0.7	μA/°C
Minimum temperature for rate accuracy	In circuit of Figure 14, I_L = 0	1.5		2	1.5		2	°C
Long term stability	$T_J = T_{MAX}$, for 1000 hours	±0.08			±0.08			°C

(1) Tested Limits are ensured and 100% tested in production.
(2) Design Limits are ensured (but not 100% production tested) over the indicated temperature and supply voltage ranges. These limits are not used to calculate outgoing quality levels.
(3) Accuracy is defined as the error between the output voltage and 10 mv/°C times the case temperature of the device, at specified conditions of voltage, current, and temperature (expressed in °C).
(4) Non-linearity is defined as the deviation of the output-voltage-versus-temperature curve from the best-fit straight line, over the rated temperature range of the device.
(5) Regulation is measured at constant junction temperature, using pulse testing with a low duty cycle. Changes in output due to heating effects can be computed by multiplying the internal dissipation by the thermal resistance.
(6) Quiescent current is defined in the circuit of Figure 14.

6.8 Electrical Characteristics: LM35, LM35C, LM35D

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 µA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS		LM35			LM35C, LM35D			UNIT
			MIN	TYP	MAX	MIN	TYP	MAX	
Accuracy, LM35, LM35C(1)	T_A = 25°C			±0.4			±0.4		°C
		Tested Limit(2)			±1			±1	
		Design Limit(3)							
	T_A = –10°C			±0.5			±0.5		
		Tested Limit(2)							
		Design Limit(3)						±1.5	
	T_A = T_{MAX}			±0.8			±0.8		
		Tested Limit(2)			±1.5				
		Design Limit(3)						±1.5	
	T_A = T_{MIN}			±0.8			±0.8		
		Tested Limit(2)							
		Design Limit(3)			±1.5			±2	
Accuracy, LM35D(1)	T_A = 25°C						±0.6		°C
		Tested Limit(2)						±1.5	
		Design Limit(3)							
	T_A = T_{MAX}						±0.9		
		Tested Limit(2)							
		Design Limit(3)						±2	
	T_A = T_{MIN}						±0.9		
		Tested Limit(2)							
		Design Limit(3)						±2	
Nonlinearity(4)	T_{MIN} ≤ T_A ≤ T_{MAX}, –40°C ≤ T_J ≤ 125°C			±0.3			±0.2		°C
		Tested Limit(2)							
		Design Limit(3)			±0.5			±0.5	
Sensor gain (average slope)	T_{MIN} ≤ T_A ≤ T_{MAX}, –40°C ≤ T_J ≤ 125°C			10			10		mV/°C
		Tested Limit(2)			9.8				
		Design Limit(3)						9.8	
				10			10		
		Tested Limit(2)			10.2				
		Design Limit(3)						10.2	
Load regulation(5) 0 ≤ I_L ≤ 1 mA	T_A = 25°C			±0.4			±0.4		mV/mA
		Tested Limit(2)			±2			±2	
		Design Limit(3)							
	T_{MIN} ≤ T_A ≤ T_{MAX}, –40°C ≤ T_J ≤ 125°C			±0.5			±0.5		
		Tested Limit(2)							
		Design Limit(3)			±5			±5	

---

(1) Accuracy is defined as the error between the output voltage and 10 mv/°C times the case temperature of the device, at specified conditions of voltage, current, and temperature (expressed in °C).
(2) Tested Limits are ensured and 100% tested in production.
(3) Design Limits are ensured (but not 100% production tested) over the indicated temperature and supply voltage ranges. These limits are not used to calculate outgoing quality levels.
(4) Non-linearity is defined as the deviation of the output-voltage-versus-temperature curve from the best-fit straight line, over the rated temperature range of the device.
(5) Regulation is measured at constant junction temperature, using pulse testing with a low duty cycle. Changes in output due to heating effects can be computed by multiplying the internal dissipation by the thermal resistance.

Electrical Characteristics: LM35, LM35C, LM35D (continued)

Unless otherwise noted, these specifications apply: −55°C ≤ T_J ≤ 150°C for the LM35 and LM35A; −40°C ≤ T_J ≤ 110°C for the LM35C and LM35CA; and 0°C ≤ T_J ≤ 100°C for the LM35D. V_S = 5 Vdc and I_{LOAD} = 50 µA, in the circuit of Full-Range Centigrade Temperature Sensor. These specifications also apply from 2°C to T_{MAX} in the circuit of Figure 14.

PARAMETER	TEST CONDITIONS		LM35			LM35C, LM35D			UNIT
			MIN	TYP	MAX	MIN	TYP	MAX	
Line regulation[5]	T_A = 25°C			±0.01			±0.01		mV/V
		Tested Limit[2]			±0.1				
		Design Limit[3]						±0.1	
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C			±0.02			±0.02		
		Tested Limit[2]							
		Design Limit[3]			±0.2			±0.2	
Quiescent current[6]	V_S = 5 V, 25°C			56			56		µA
		Tested Limit[2]			80			80	
		Design Limit[3]							
	V_S = 5 V, –40°C ≤ T_J ≤ 125°C			105			91		
		Tested Limit[2]							
		Design Limit[3]			158			138	
	V_S = 30 V, 25°C			56.2			56.2		
		Tested Limit[2]			82			82	
		Design Limit[3]							
	V_S = 30 V, –40°C ≤ T_J ≤ 125°C			105.5			91.5		
		Tested Limit[2]							
		Design Limit[3]			161			141	
Change of quiescent current[5]	4 V ≤ V_S ≤ 30 V, 25°C			0.2			0.2		µA
		Tested Limit[2]						2	
		Design Limit[3]			2				
	4 V ≤ V_S ≤ 30 V, –40°C ≤ T_J ≤ 125°C			0.5			0.5		
		Tested Limit[2]							
		Design Limit[3]			3			3	
Temperature coefficient of quiescent current	–40°C ≤ T_J ≤ 125°C			0.39			0.39		µA/°C
		Tested Limit[2]							
		Design Limit[3]			0.7			0.7	
Minimum temperature for rate accuracy	In circuit of Figure 14, I_L = 0			1.5			1.5		°C
		Tested Limit[2]							
		Design Limit[3]			2			2	
Long term stability	T_J = T_{MAX}, for 1000 hours			±0.08			±0.08		°C

(6) Quiescent current is defined in the circuit of Figure 14.

6.9 Typical Characteristics

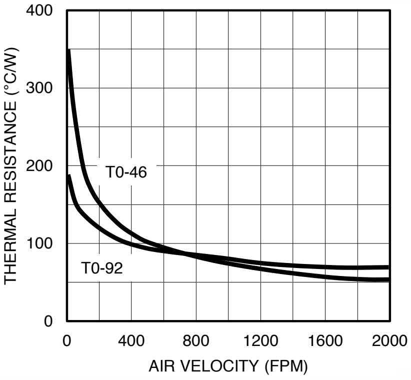


Figure 1. Thermal Resistance Junction To Air

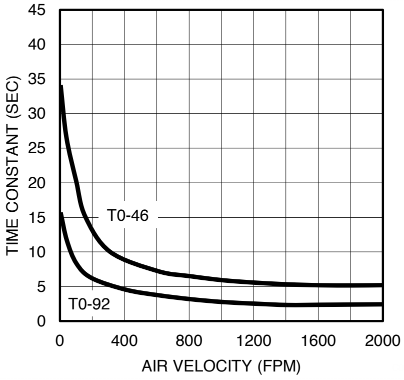


Figure 2. Thermal Time Constant

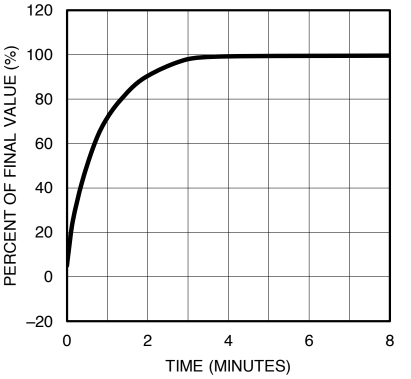


Figure 3. Thermal Response In Still Air

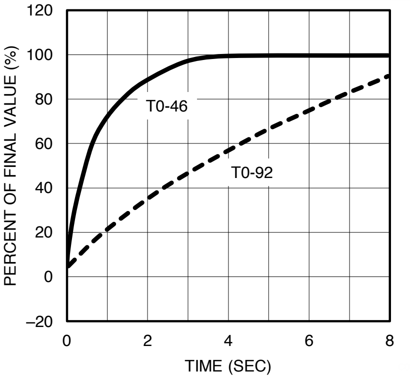


Figure 4. Thermal Response In Stirred Oil Bath

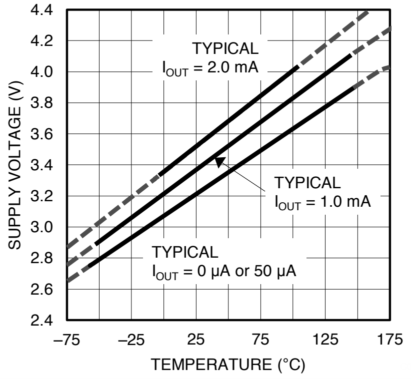


Figure 5. Minimum Supply Voltage vs Temperature

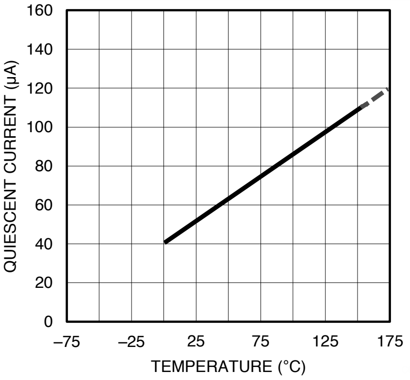


Figure 6. Quiescent Current vs Temperature (in Circuit of Figure 14)

Typical Characteristics (continued)

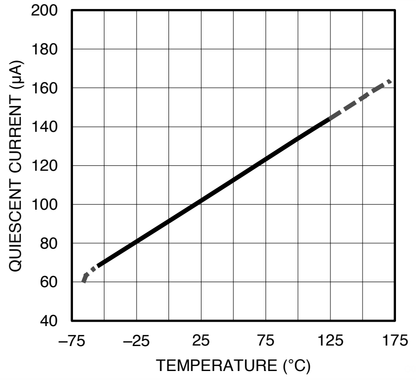


Figure 7. Quiescent Current vs Temperature (in Circuit of Full-Range Centigrade Temperature Sensor)

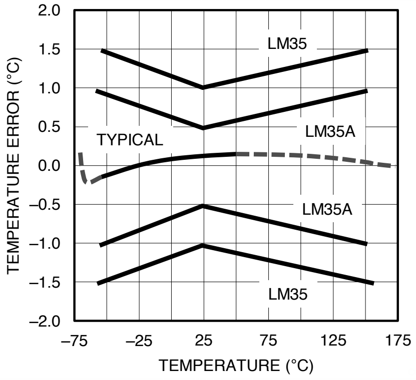


Figure 8. Accuracy vs Temperature (Ensured)

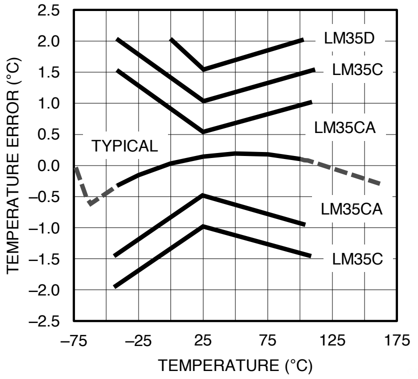


Figure 9. Accuracy vs Temperature (Ensured)

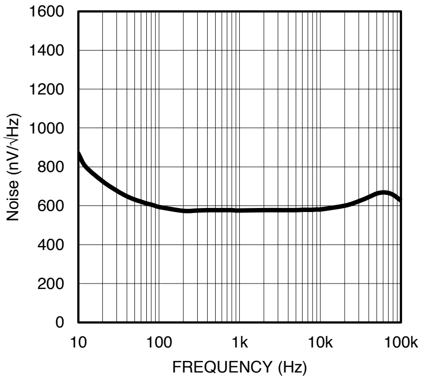


Figure 10. Noise Voltage

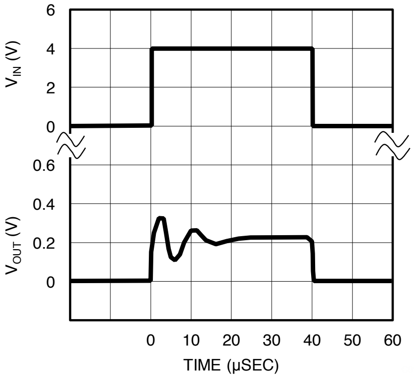


Figure 11. Start-Up Response

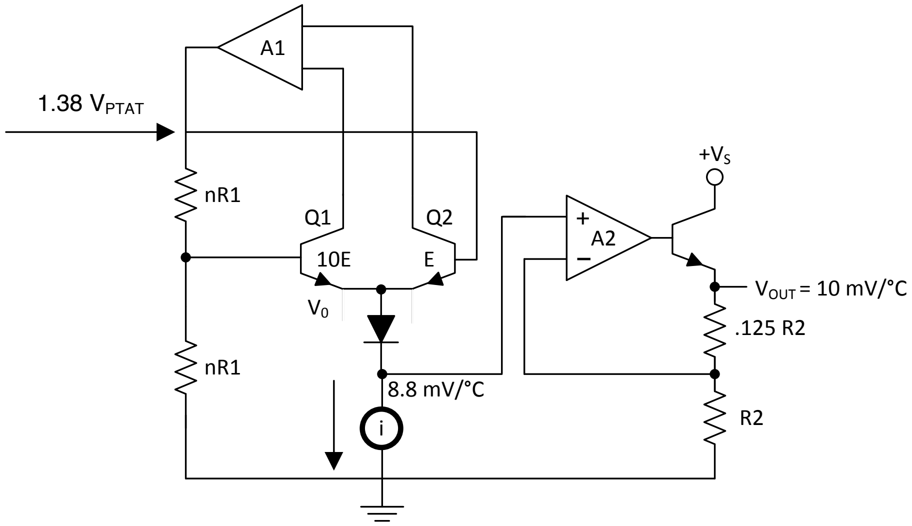
7 Detailed Description

7.1 Overview

The LM35-series devices are precision integrated-circuit temperature sensors, with an output voltage linearly proportional to the Centigrade temperature. The LM35 device has an advantage over linear temperature sensors calibrated in Kelvin, as the user is not required to subtract a large constant voltage from the output to obtain convenient Centigrade scaling. The LM35 device does not require any external calibration or trimming to provide typical accuracies of ± ¼ °C at room temperature and ± ¾ °C over a full −55°C to 150°C temperature range. Lower cost is assured by trimming and calibration at the wafer level. The low output impedance, linear output, and precise inherent calibration of the LM35 device makes interfacing to readout or control circuitry especially easy. The device is used with single power supplies, or with plus and minus supplies. As the LM35 device draws only 60 µA from the supply, it has very low self-heating of less than 0.1°C in still air. The LM35 device is rated to operate over a −55°C to 150°C temperature range, while the LM35C device is rated for a −40°C to 110°C range (−10° with improved accuracy). The temperature-sensing element is comprised of a delta-V BE architecture.

The temperature-sensing element is then buffered by an amplifier and provided to the VOUT pin. The amplifier has a simple class A output stage with typical 0.5-Ω output impedance as shown in the *Functional Block Diagram*. Therefore the LM35 can only source current and it's sinking capability is limited to 1 µA.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 LM35 Transfer Function

The accuracy specifications of the LM35 are given with respect to a simple linear transfer function:

V_{OUT} = 10 mv/°F × T

where

- V_{OUT} is the LM35 output voltage
- T is the temperature in °C (1)

7.4 Device Functional Modes

The only functional mode of the LM35 is that it has an analog output directly proportional to temperature.

8 Application and Implementation

NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

8.1 Application Information

The features of the LM35 make it suitable for many general temperature sensing applications. Multiple package options expand on it's flexibility.

8.1.1 Capacitive Drive Capability

Like most micropower circuits, the LM35 device has a limited ability to drive heavy capacitive loads. Alone, the LM35 device is able to drive 50 pF without special precautions. If heavier loads are anticipated, isolating or decoupling the load with a resistor is easy (see Figure 12). The tolerance of capacitance can be improved with a series R-C damper from output to ground (see Figure 13).

When the LM35 device is applied with a 200-Ω load resistor as shown in Figure 16, Figure 17, or Figure 19, the device is relatively immune to wiring capacitance because the capacitance forms a bypass from ground to input and not on the output. However, as with any linear circuit connected to wires in a hostile environment, performance is affected adversely by intense electromagnetic sources (such as relays, radio transmitters, motors with arcing brushes, and SCR transients), because the wiring acts as a receiving antenna and the internal junctions act as rectifiers. For best results in such cases, a bypass capacitor from V_{IN} to ground and a series R-C damper, such as 75 Ω in series with 0.2 or 1 μF from output to ground, are often useful. Examples are shown in Figure 13, Figure 24, and Figure 25.

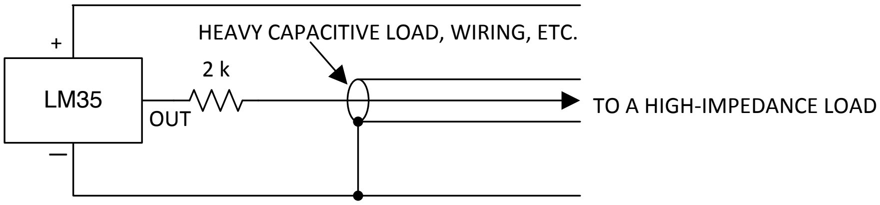


Figure 12. LM35 with Decoupling from Capacitive Load

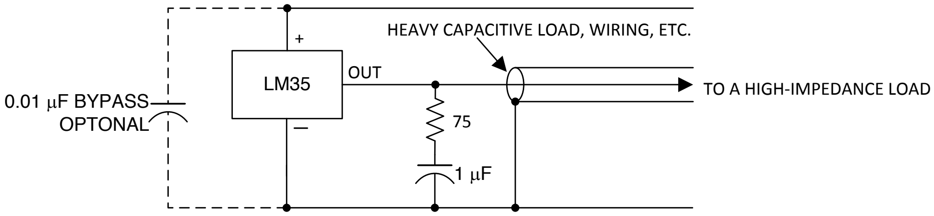


Figure 13. LM35 with R-C Damper

8.2 Typical Application

8.2.1 Basic Centigrade Temperature Sensor

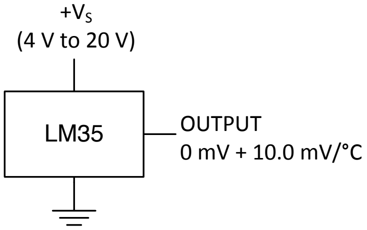


Figure 14. Basic Centigrade Temperature Sensor (2 °C to 150 °C)

8.2.1.1 Design Requirements

Table 1. Design Parameters

PARAMETER	VALUE
Accuracy at 25°C	±0.5°C
Accuracy from –55 °C to 150°C	±1°C
Temperature Slope	10 mV/°C

8.2.1.2 Detailed Design Procedure

Because the LM35 device is a simple temperature sensor that provides an analog output, design requirements related to layout are more important than electrical requirements. For a detailed description, refer to the *Layout*.

8.2.1.3 Application Curve

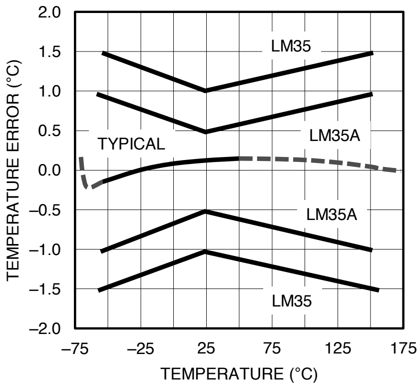


Figure 15. Accuracy vs Temperature (Ensured)

8.3 System Examples

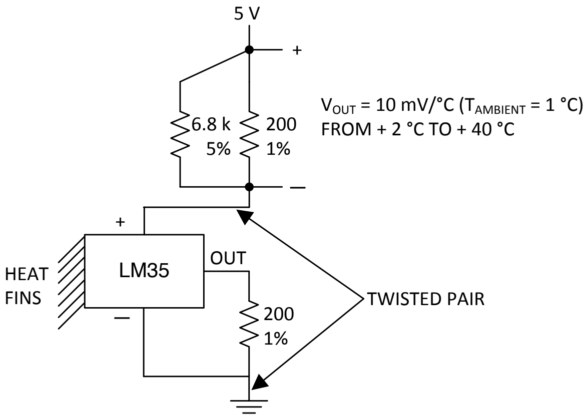


Figure 16. Two-Wire Remote Temperature Sensor (Grounded Sensor)

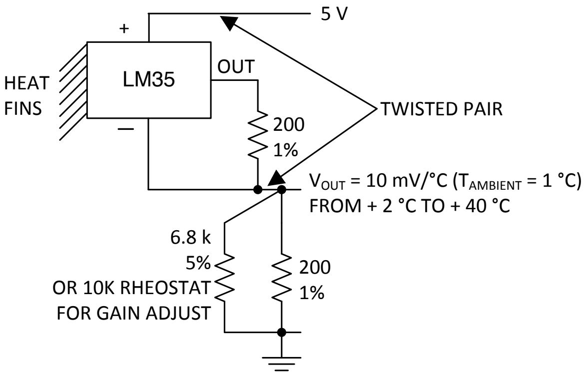


Figure 17. Two-Wire Remote Temperature Sensor (Output Referred to Ground)

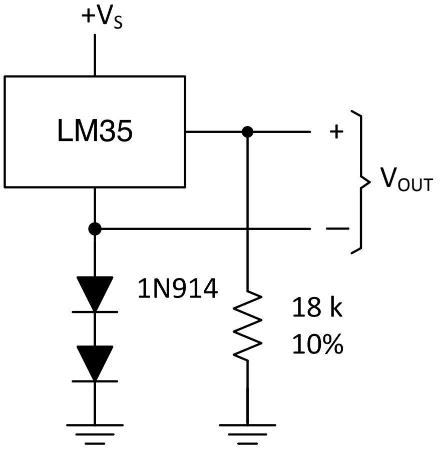


Figure 18. Temperature Sensor, Single Supply (−55° to +150°C)

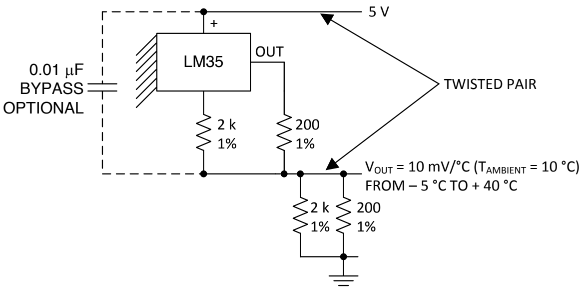


Figure 19. Two-Wire Remote Temperature Sensor (Output Referred to Ground)

System Examples (continued)

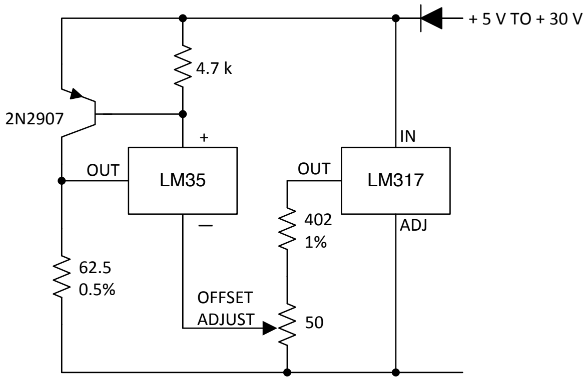


Figure 20. 4-To-20 mA Current Source (0°C to 100°C)

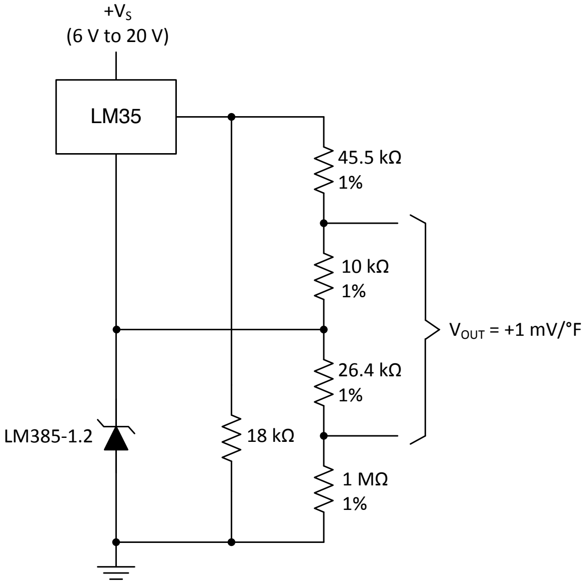


Figure 21. Fahrenheit Thermometer

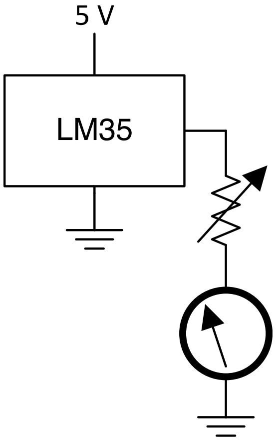


Figure 22. Centigrade Thermometer (Analog Meter)

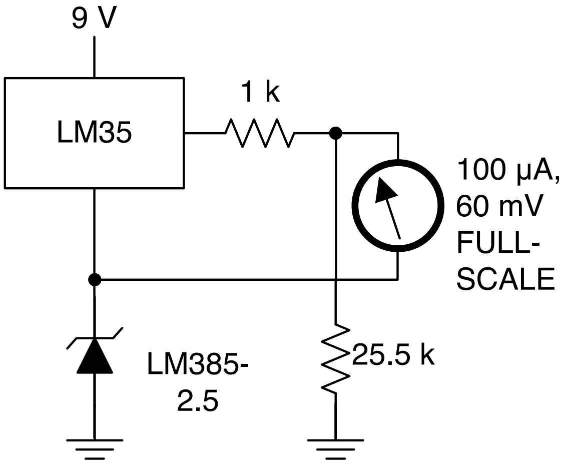


Figure 23. Fahrenheit Thermometer, Expanded Scale Thermometer (50°F to 80°F, for Example Shown)

System Examples (continued)

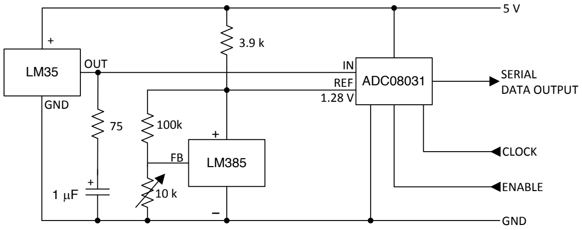


Figure 24. Temperature to Digital Converter (Serial Output) (128°C Full Scale)

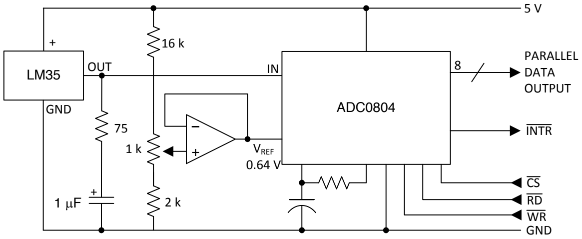
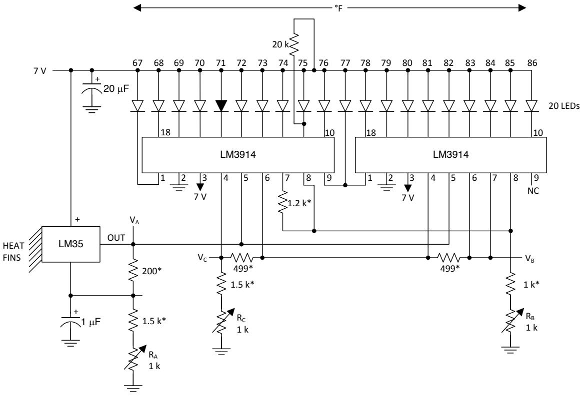


Figure 25. Temperature to Digital Converter (Parallel TRI-STATE Outputs for Standard Data Bus to µP Interface) (128°C Full Scale)



*=1% or 2% film resistor

Trim R_B for V_B = 3.075 V

Trim R_C for V_C = 1.955 V

Trim R_A for V_A = 0.075 V + 100 mV/°C ×$T_{ambient}$

Example, V_A = 2.275 V at 22°C

Figure 26. Bar-Graph Temperature Display (Dot Mode)

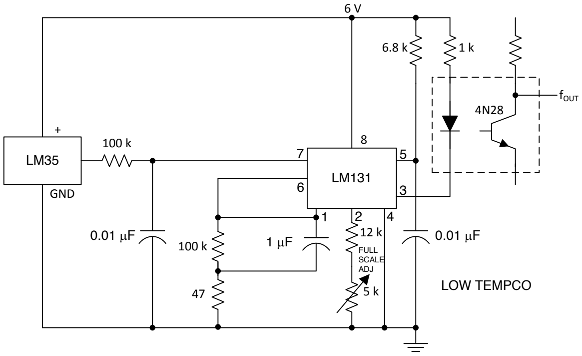


Figure 27. LM35 With Voltage-To-Frequency Converter and Isolated Output (2°C to 150°C; 20 to 1500 Hz)

9 Power Supply Recommendations

The LM35 device has a very wide 4-V to 5.5-V power supply voltage range, which makes it ideal for many applications. In noisy environments, TI recommends adding a 0.1 μF from V+ to GND to bypass the power supply voltage. Larger capacitances maybe required and are dependent on the power-supply noise.

10 Layout

10.1 Layout Guidelines

The LM35 is easily applied in the same way as other integrated-circuit temperature sensors. Glue or cement the device to a surface and the temperature should be within about 0.01°C of the surface temperature.

The 0.01°C proximity presumes that the ambient air temperature is almost the same as the surface temperature. If the air temperature were much higher or lower than the surface temperature, the actual temperature of the LM35 die would be at an intermediate temperature between the surface temperature and the air temperature; this is especially true for the TO-92 plastic package. The copper leads in the TO-92 package are the principal thermal path to carry heat into the device, so its temperature might be closer to the air temperature than to the surface temperature.

Ensure that the wiring leaving the LM35 device is held at the same temperature as the surface of interest to minimize the temperature problem. The easiest fix is to cover up these wires with a bead of epoxy. The epoxy bead will ensure that the leads and wires are all at the same temperature as the surface, and that the temperature of the LM35 die is not affected by the air temperature.

The TO-46 metal package can also be soldered to a metal surface or pipe without damage. Of course, in that case the V− terminal of the circuit will be grounded to that metal. Alternatively, mount the LM35 inside a sealed-end metal tube, and then dip into a bath or screw into a threaded hole in a tank. As with any IC, the LM35 device and accompanying wiring and circuits must be kept insulated and dry, to avoid leakage and corrosion. This is especially true if the circuit may operate at cold temperatures where condensation can occur. Printed-circuit coatings and varnishes such as a conformal coating and epoxy paints or dips are often used to insure that moisture cannot corrode the LM35 device or its connections.

These devices are sometimes soldered to a small light-weight heat fin to decrease the thermal time constant and speed up the response in slowly-moving air. On the other hand, a small thermal mass may be added to the sensor, to give the steadiest reading despite small deviations in the air temperature.

Table 2. Temperature Rise of LM35 Due To Self-heating (Thermal Resistance, $R_{\theta JA}$)

	TO, no heat sink	TO[1], small heat fin	TO-92, no heat sink	TO-92[2], small heat fin	SOIC-8, no heat sink	SOIC-8[2], small heat fin	TO-220, no heat sink
Still air	400°C/W	100°C/W	180°C/W	140°C/W	220°C/W	110°C/W	90°C/W
Moving air	100°C/W	40°C/W	90°C/W	70°C/W	105°C/W	90°C/W	26°C/W
Still oil	100°C/W	40°C/W	90°C/W	70°C/W	—	—	—
Stirred oil	50°C/W	30°C/W	45°C/W	40°C/W	—	—	—
(Clamped to metal, Infinite heat sink)	(24°C/W)		—	—	(55°C/W)		—

(1) Wakefield type 201, or 1-in disc of 0.02-in sheet brass, soldered to case, or similar.
(2) TO-92 and SOIC-8 packages glued and leads soldered to 1-in square of 1/16-in printed circuit board with 2-oz foil or similar.

10.2 Layout Example

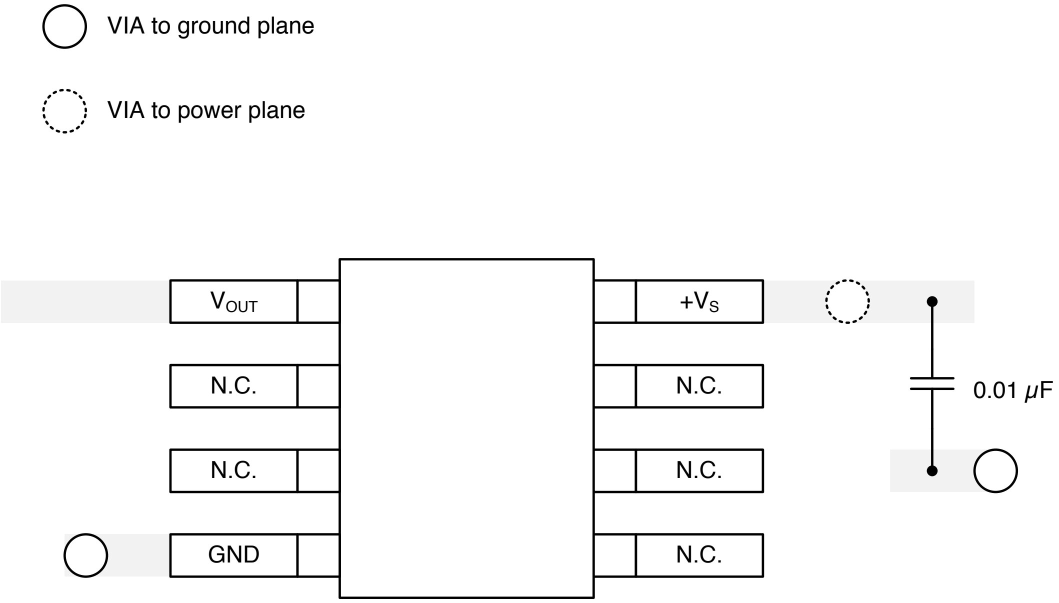


Figure 28. Layout Example

11 Device and Documentation Support

11.1 Trademarks

All trademarks are the property of their respective owners.

11.2 Electrostatic Discharge Caution

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

11.3 Glossary

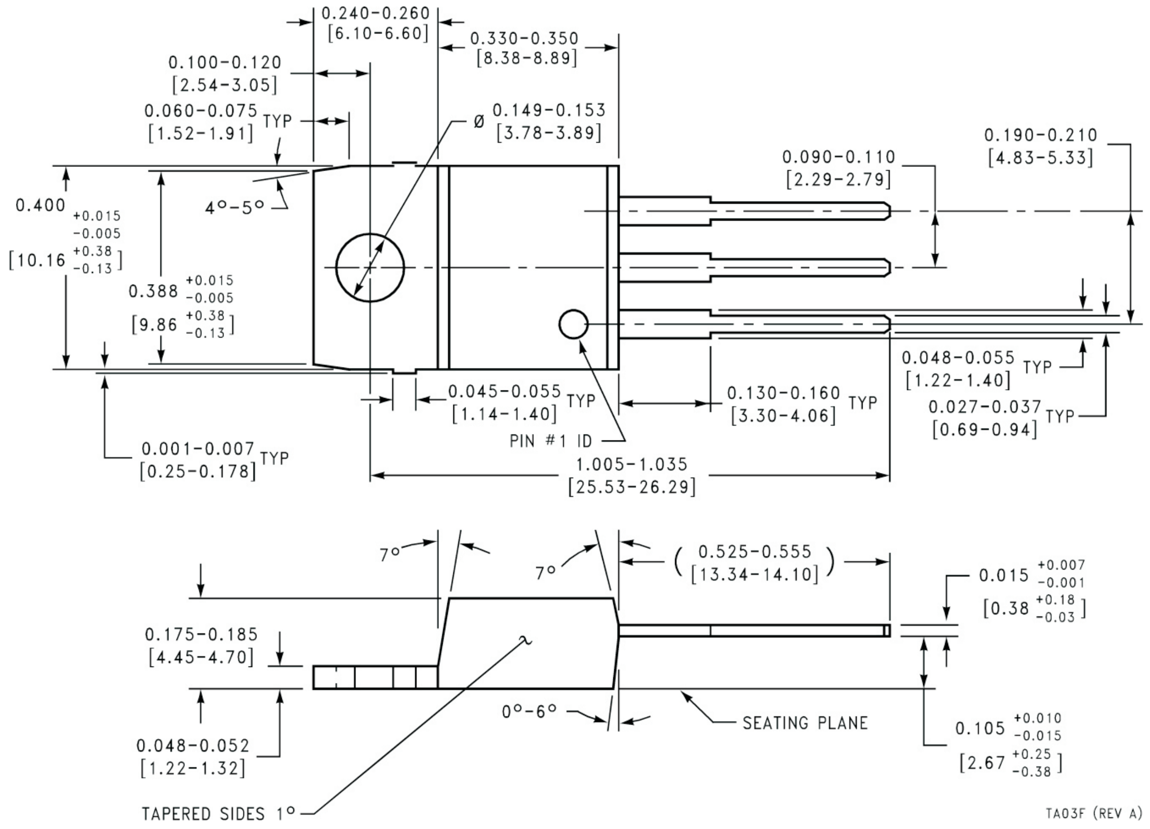
SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

NEB0003F


0.240–0.260
[6.10–6.60]
0.330–0.350
[8.38–8.89]
0.100–0.120
[2.54–3.05]
0.060–0.075
[1.52–1.91]
TYP
Ø 0.149–0.153
[3.78–3.89]
0.090–0.110
[2.29–2.79]
0.190–0.210
[4.83–5.33]
0.400 +0.015 −0.005
[10.16 +0.38 −0.13]
4°–5°
0.388 +0.015 −0.005
[9.86 +0.38 −0.13]
0.048–0.055 TYP
[1.22–1.40]
0.027–0.037 TYP
[0.69–0.94]
0.045–0.055 TYP
[1.14–1.40]
0.130–0.160 TYP
[3.30–4.06]
PIN #1 ID
0.001–0.007 TYP
[0.25–0.178]
1.005–1.035
[25.53–26.29]
7°
7°
(0.525–0.555
[13.34–14.10])
0.015 +0.007 −0.001
[0.38 +0.18 −0.03]
0.175–0.185
[4.45–4.70]
0°–6°
SEATING PLANE
0.105 +0.010 −0.015
[2.67 +0.25 −0.38]
0.048–0.052
[1.22–1.32]
TAPERED SIDES 1°
TA03F (REV A)

PACKAGE OPTION ADDENDUM

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
LM35AH	ACTIVE	TO	NDV	3		TBD	Call TI	Call TI	-55 to 150	(LM35AH ~ LM35AH)	Samples
LM35AH/NOPB	ACTIVE	TO	NDV	3	500	Green (RoHS & no Sb/Br)	Call TI	Level-1-NA-UNLIM	-55 to 150	(LM35AH ~ LM35AH)	Samples
LM35CAH	ACTIVE	TO	NDV	3	500	TBD	Call TI	Call TI	-40 to 110	(LM35CAH ~ LM35CAH)	Samples
LM35CAH/NOPB	ACTIVE	TO	NDV	3	500	Green (RoHS & no Sb/Br)	Call TI	Level-1-NA-UNLIM	-40 to 110	(LM35CAH ~ LM35CAH)	Samples
LM35CAZ/LFT4	ACTIVE	TO-92	LP	3	2000	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type		LM35 CAZ	Samples
LM35CAZ/NOPB	ACTIVE	TO-92	LP	3	1800	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type	-40 to 110	LM35 CAZ	Samples
LM35CH	ACTIVE	TO	NDV	3	500	TBD	Call TI	Call TI	-40 to 110	(LM35CH ~ LM35CH)	Samples
LM35CH/NOPB	ACTIVE	TO	NDV	3	500	Green (RoHS & no Sb/Br)	Call TI	Level-1-NA-UNLIM	-40 to 110	(LM35CH ~ LM35CH)	Samples
LM35CZ/LFT1	ACTIVE	TO-92	LP	3	2000	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type		LM35 CZ	Samples
LM35CZ/NOPB	ACTIVE	TO-92	LP	3	1800	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type	-40 to 110	LM35 CZ	Samples
LM35DH	ACTIVE	TO	NDV	3	1000	TBD	Call TI	Call TI	0 to 70	(LM35DH ~ LM35DH)	Samples
LM35DH/NOPB	ACTIVE	TO	NDV	3	1000	Green (RoHS & no Sb/Br)	Call TI I POST-PLATE	Level-1-NA-UNLIM	0 to 70	(LM35DH ~ LM35DH)	Samples
LM35DM	NRND	SOIC	D	8	95	TBD	Call TI	Call TI	0 to 100	LM35D M	
LM35DM/NOPB	ACTIVE	SOIC	D	8	95	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	0 to 100	LM35D M	Samples
LM35DMX	NRND	SOIC	D	8	2500	TBD	Call TI	Call TI	0 to 100	LM35D M	
LM35DMX/NOPB	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU SN	Level-1-260C-UNLIM	0 to 100	LM35D M	Samples
LM35DT	NRND	TO-220	NEB	3	45	TBD	Call TI	Call TI	0 to 100	LM35DT	
LM35DT/NOPB	ACTIVE	TO-220	NEB	3	45	Green (RoHS & no Sb/Br)	CU SN	Level-1-NA-UNLIM	0 to 100	LM35DT	Samples

PACKAGE OPTION ADDENDUM

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
LM35DZ	OBSOLETE	TO-92	LP	3		TBD	Call TI	Call TI			
LM35DZ/LFT1	ACTIVE	TO-92	LP	3	2000	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type		LM35 DZ	Samples
LM35DZ/LFT4	ACTIVE	TO-92	LP	3	2000	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type		LM35 DZ	Samples
LM35DZ/NOPB	ACTIVE	TO-92	LP	3	1800	Green (RoHS & no Sb/Br)	CU SN	N / A for Pkg Type	0 to 100	LM35 DZ	Samples
LM35H	ACTIVE	TO	NDV	3	500	TBD	Call TI	Call TI	-55 to 150	(LM35H ~ LM35H)	Samples
LM35H/NOPB	ACTIVE	TO	NDV	3	500	Green (RoHS & no Sb/Br)	Call TI	Level-1-NA-UNLIM	-55 to 150	(LM35H ~ LM35H)	Samples

[1] The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

[2] Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

[3] MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

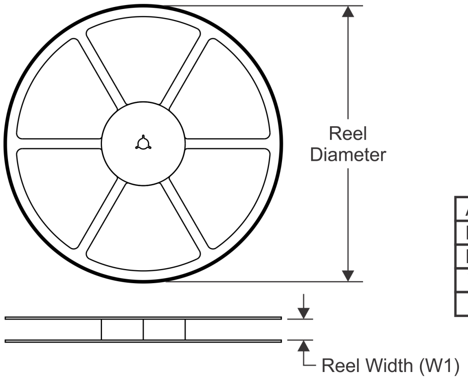
[4] There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

[5] Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

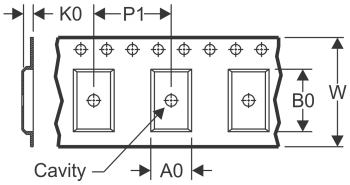
[6] Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

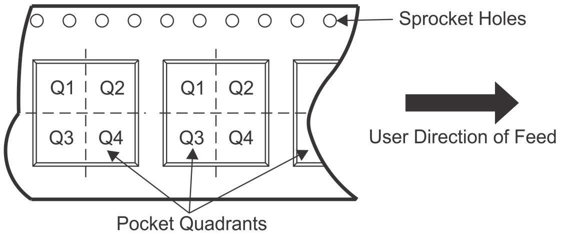


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

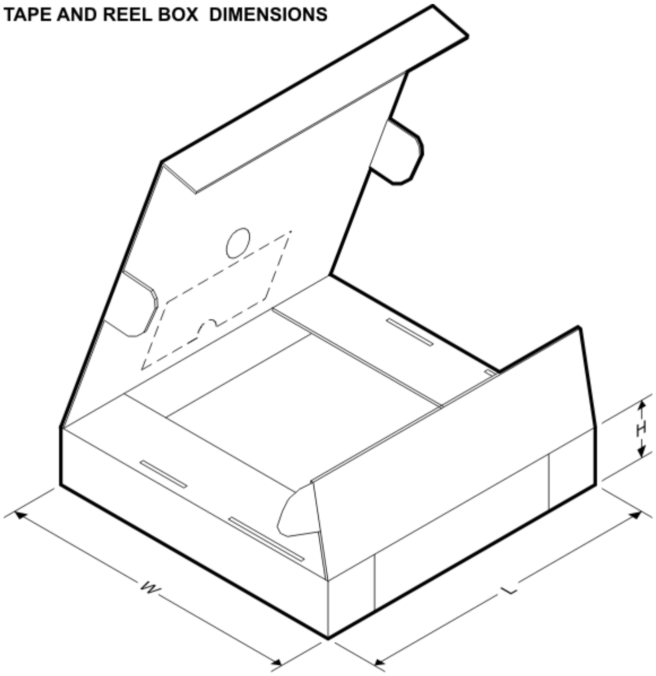
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
LM35DMX	SOIC	D	8	2500	330.0	12.4	6.5	5.4	2.0	8.0	12.0	Q1
LM35DMX/NOPB	SOIC	D	8	2500	330.0	12.4	6.5	5.4	2.0	8.0	12.0	Q1

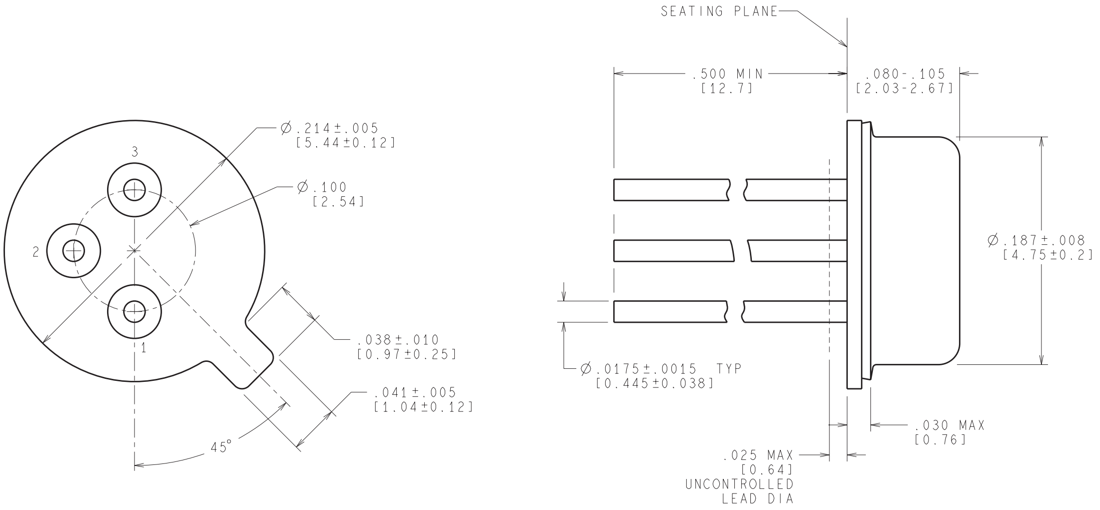
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
LM35DMX	SOIC	D	8	2500	367.0	367.0	35.0
LM35DMX/NOPB	SOIC	D	8	2500	367.0	367.0	35.0

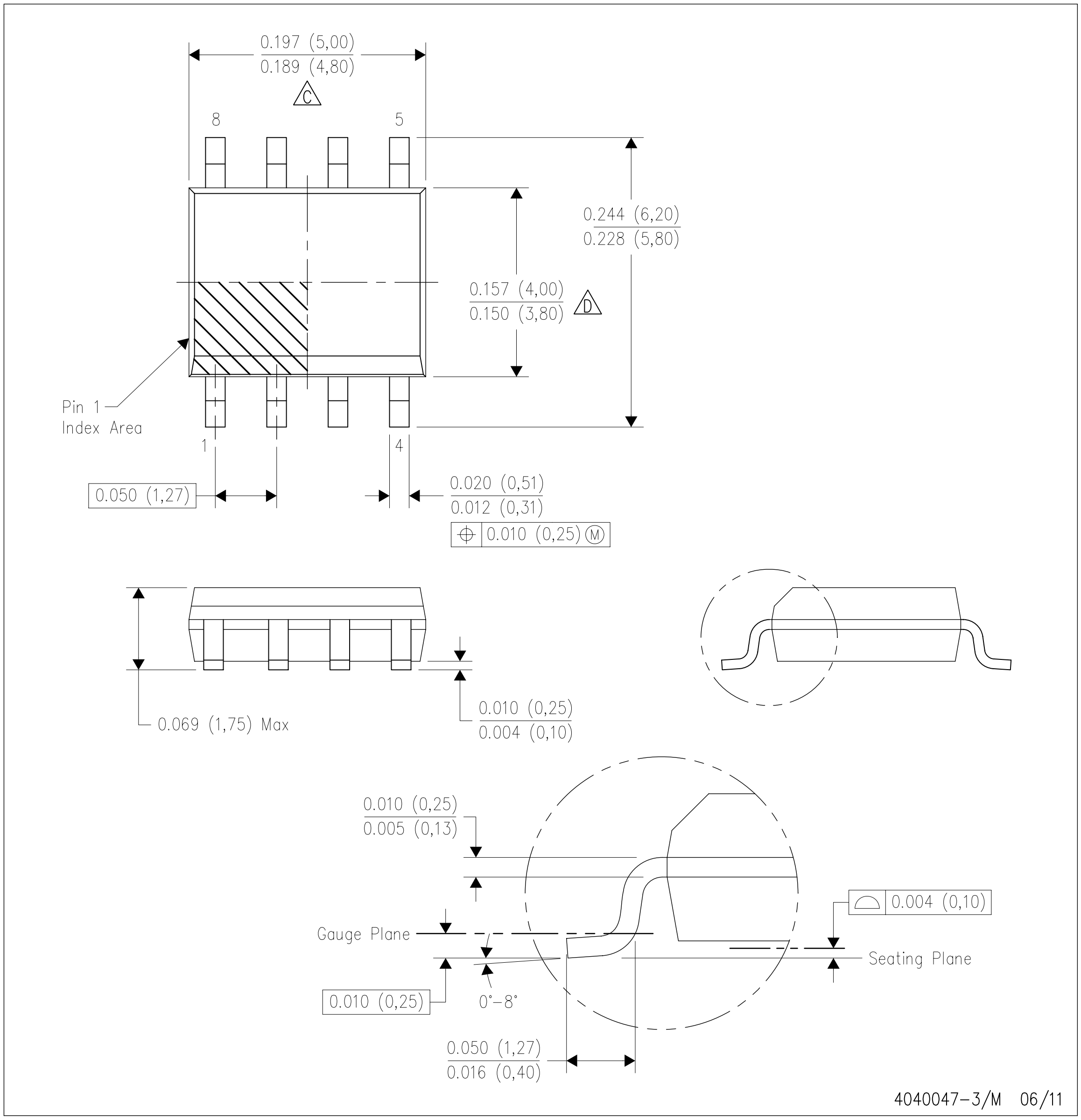
NDV0003H



CONTROLLING DIMENSION IS INCH
VALUES IN [ ] ARE IN MILLIMETERS

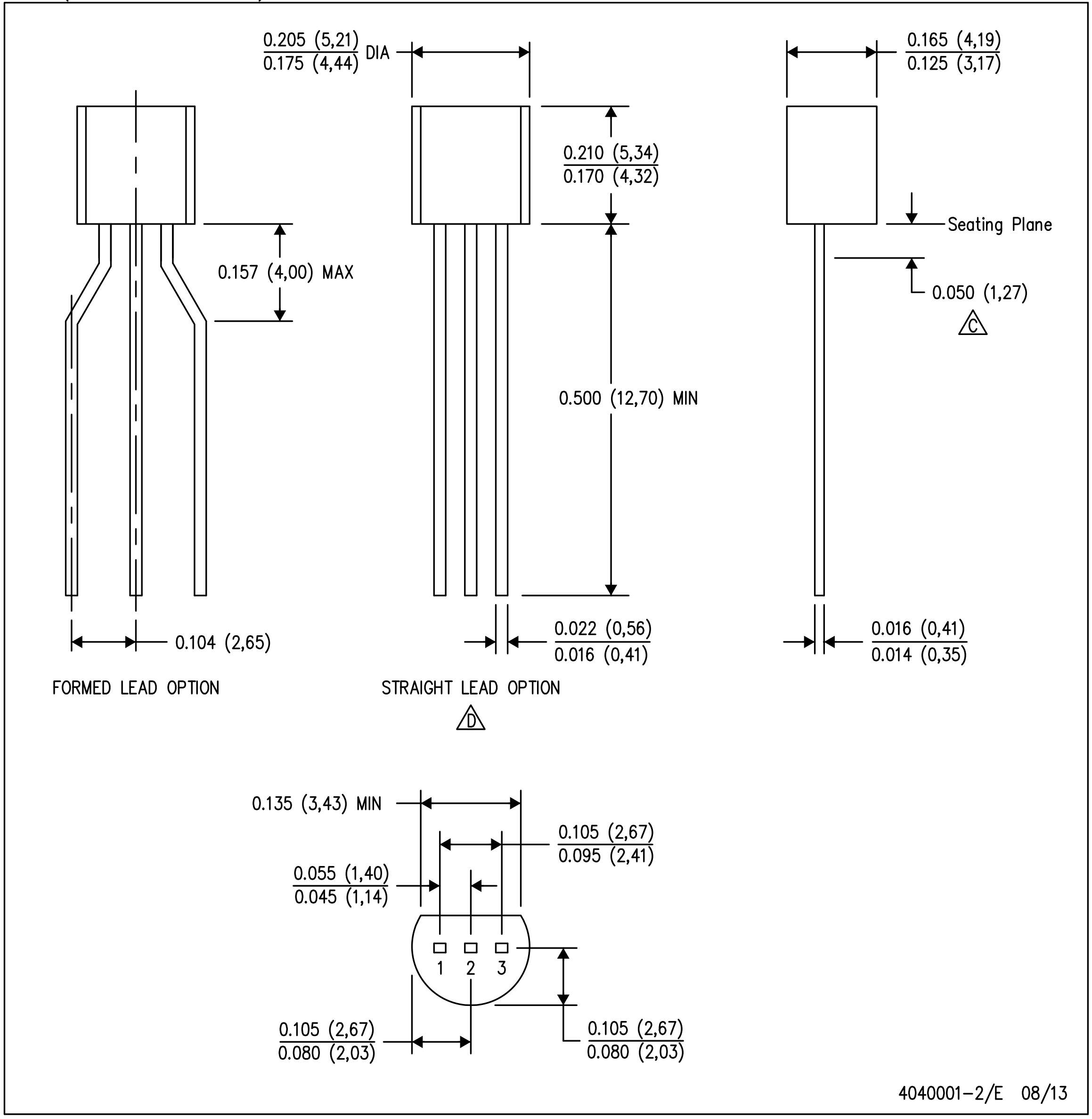
H03H (Rev F)

D (R–PDSO–G8) PLASTIC SMALL OUTLINE



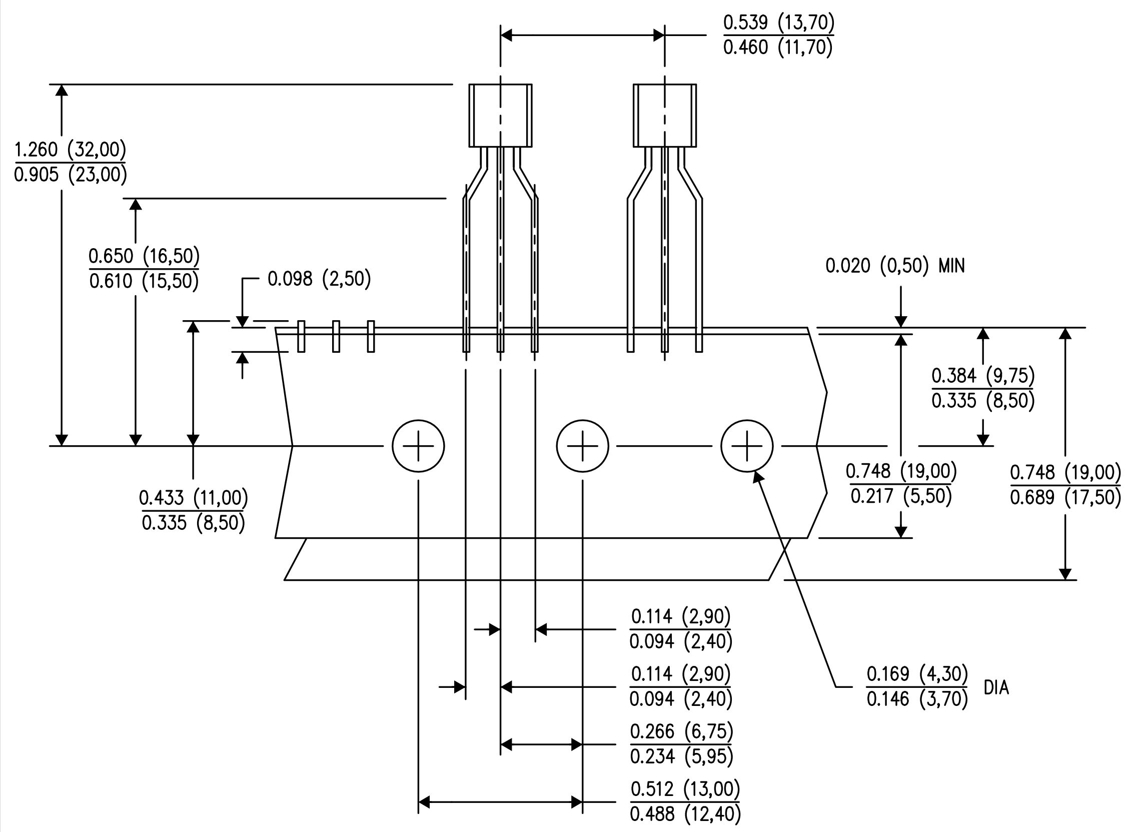
NOTES:
- A. All linear dimensions are in inches (millimeters).
- B. This drawing is subject to change without notice.
- C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.006 (0,15) each side.
- D. Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
- E. Reference JEDEC MS–012 variation AA.

LP (O–PBCY–W3) PLASTIC CYLINDRICAL PACKAGE



NOTES:
- A. All linear dimensions are in inches (millimeters).
- B. This drawing is subject to change without notice.
- C. Lead dimensions are not controlled within this area.
- D. Falls within JEDEC TO–226 Variation AA (TO–226 replaces TO–92).
- E. Shipping Method:
  Straight lead option available in bulk pack only.
  Formed lead option available in tape & reel or ammo pack.
  Specific products can be offered in limited combinations of shipping mediums and lead options.
  Consult product folder for more information on available options.

LP (O-PBCY-W3) PLASTIC CYLINDRICAL PACKAGE



TAPE & REEL

4040001-3/E 08/13

NOTES:
- A. All linear dimensions are in inches (millimeters).
- B. This drawing is subject to change without notice.
- C. Tape and Reel information for the Formed Lead Option package.

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Products		**Applications**	
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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

OMRON®

PCB Relay

G5LE

A Cubic, Single-pole 10-A Power Relay

- Subminiature “sugar cube” relay
- Contact ratings of 10 A
- Withstands impulses of up to 4,500 V
- Two types of seal available: flux protection and plastic-sealed
- UL class-B insulation certified, UL class-F available
- Ideal for applications in security equipment, household electrical appliances, garage door openers, and audio equipment

Ordering Information

To Order: Select the part number and add the desired coil voltage rating, (e.g., G5LE-1-*DC12*).

		Part number		
		Contact material		
Seal	Contact form	$AgSnO_2$	AgCdO	AgSnIn
Flux protection	SPDT	**G5LE-1**	**G5LE-1-ACD**	**G5LE-1-ASI**
	SPST-NO	**G5LE-1A**	**G5LE-1A-ACD**	**G5LE-1A-ASI**
Plastic-sealed	SPDT	**G5LE-14**	**G5LE-14-ACD**	**G5LE-14-ASI**
	SPST-NO	**G5LE-1A4**	**G5LE-1A4-ACD**	**G5LE-1A4-ASI**

MODEL NUMBER LEGEND

G5LE-☐ ☐ ☐-☐ -☐
1 2 3 4 5

1. **Number of Poles**
   1: 1 pole
2. **Contact Form**
   None: SPDT
   A: SPST-NO
3. **Sealing**
   None: Flux-protection
   4: Plastic-sealed
4. **Contact Material**
   None: $AgSnO_2$
   ACD: AgCdO
   ASI: AgSnIn
5. **Insulation Class**
   None: Class B insulation
   CF: Class F insulation

Specifications

COIL DATA

Rated voltage	3 VDC	5 VDC	6 VDC	9 VDC	12 VDC	24 VDC	48 VDC
Rated current	136.4 mA	79.4 mA	66.7 mA	45 mA	33.3 mA	16.7 mA	8.33 mA
Coil resistance	22.5 Ω	63 Ω	90 Ω	200 Ω	360 Ω	1,440 Ω	5,760 Ω
Must operate voltage	75% of rated voltage (max.)						
Must release voltage	10% of rated voltage (min.)						
Max. voltage	130% of rated voltage at 70°C (158°F), 170% of rated voltage at 23°C (73°F)						
Power consumption	Approx. 400 mW						

Note: 1. The rated current and coil resistance are measured at a coil temperature of 23°C (73°F) with a tolerance of ±10%.
2. 360 mW coil is available. Contact Omron for details.
3. VDE approved model available. Contact Omron for details.

CONTACT DATA

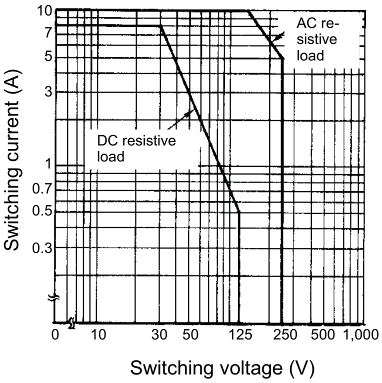
Load		Resistive load (cosφ = 1)
Rated load		10 A at 120 VAC; 8 A at 30 VDC
Rated carry current		10 A
Max. switching voltage		250 VAC, 125 VDC
Max. switching current	AC	10 A
	DC	8 A
Max. switching capacity		1,200 VA, 240 W
Min. permissible load		100 mA at 5 VDC

CHARACTERISTICS

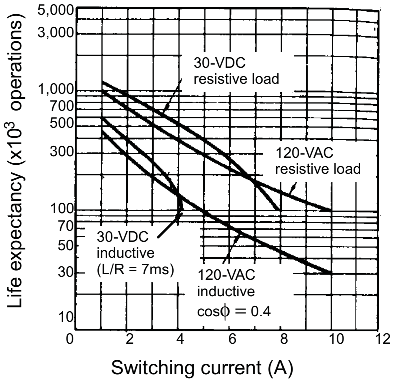
Contact resistance		100 mΩ max.
Operate time		10 ms max.
Release time		5 ms max.
Bounce time	Operate	Approx. 0.6 ms
	Release	Approx. 7.2 ms
Max. switching frequency	Mechanical	18,000 operations/hr
	Electrical	1,800 operations/hr (under rated load)
Insulation resistance		100 MΩ min. (at 500 VDC)
Dielectric strength		750 VAC, 50/60 Hz for 1 min between contacts of same polarity 2,000 VAC, 50/60 Hz for 1 min between coil and contacts
Impulse withstand voltage		4,500 V between coil and contacts
Vibration resistance	Destruction	10 to 55 Hz, 1.5-mm double amplitude
	Malfunction	10 to 55 Hz, 1.5-mm double amplitude
Shock resistance	Destruction	1,000 m/s^2 (approx. 100G)
	Malfunction	100 m/s^2 (approx. 10G)
Life expectancy	Mechanical	10,000,000 operations min. (at 18,000 operations/hr)
	Electrical	100,000 operations min. (at 1,800 operations/hr)
Ambient temperature	Operating	–40°C to 85°C (–13°F to 185°F)
Ambient humidity		35% to 85%
Weight		Approx. 12 g (0.42 oz)

CHARACTERISTIC DATA

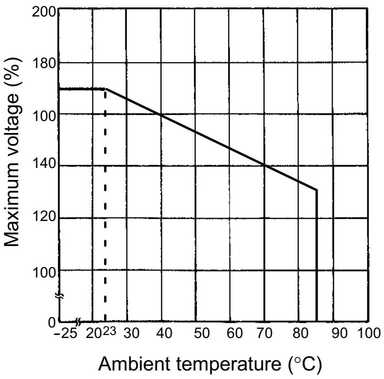
Max. Switching Capacity G5LE



Life Expectancy G5LE



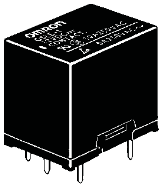
Ambient Temperature vs. Maximum Voltage

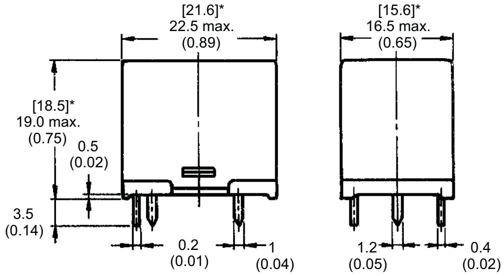


Dimensions

Unit: mm (inch)

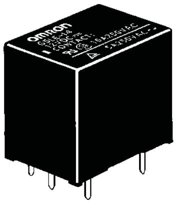
G5LE-1(A)

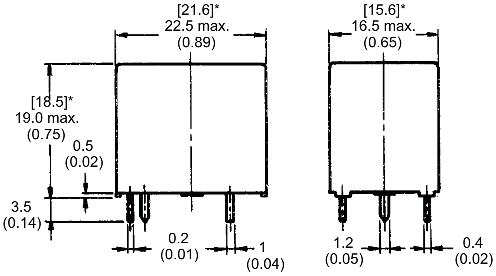




*Average value

G5LE-1(A)4





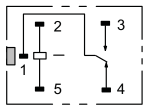
*Average value

STANDARD

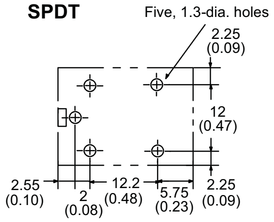
Terminal Arrangement/ Internal Connections (Bottom View)

Mounting Holes (Bottom View)
Tolerance: ±0.1 mm

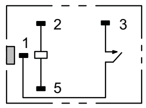
SPDT



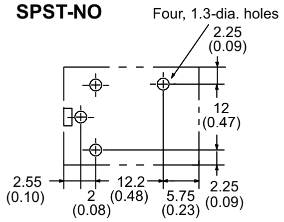
SPDT



SPST-NO



SPST-NO



Note: Orientation marks are indicated as follows: ▨ □

APPROVALS

UL325, UL508, UL1409, UL1950 (File No. E41643)

Part number	Coil rating	Contact rating
G5LE	3 to 48 VDC	5 A, 250 VAC (general use) 5 A, 30 VDC (resistive load) 125 VA, 120 VAC (P.D 100,000 cycles) 5 A, 125 VAC (G.P), 30K, 70°C (158°F) NO: 1/8 hp, 120 VAC (50,000 cycles) 4 FLA, 4 LRA, 120 VAC (100,000 cycles) 1/2 s, ON:OFF Ambient temperature: 105°C (221°F) 5 FLA, 30 LRA, 120 VAC Mechanical life: 100,000 cycles TV-3, 120 VAC NC: 1/10 hp, 120 VAC (50,000 cycles) 2 FLA, 4 LRA, 120 VAC (100,000 cycles) 1/2 s, ON:OFF Ambient temperature: 105°C (221°F)
		10 A, 250 VAC (general use) 8 A, 30 VDC (resistive load) NO: 1/6 hp, 120 VAC (50,000 cycles) 1/3 hp, 125 VAC, 30K, 70°C (158°F) NC: 1/8 hp, 120 VAC (50,000 cycles)

Note: Only part numbers with the suffix “ASI” are TV-5 approved.

CSA C22.2 NO. 14 (File No. LR34815)

Part number	Coil rating	Contact rating
G5LE	3 to 48 VDC	5 A, 250 VAC (general use) 5 A, 30 VDC (resistive load) 125 VA, 120 VAC (P.D 100,000 cycles) 5 A, 125 VAC (G.P), 30K, 70°C (158°F) NO: 1/8 hp, 120 VAC (50,000 cycles) TV-3 NC: 1/10 hp, 120 VAC (50,000 cycles)
		10 A, 250 VAC (general use) 8 A, 30 VDC (resistive load) 6 A, 277 VAC (general use), 100K NO: 1/6 hp, 120 VAC (50,000 cycles) 1/3 hp, 125 VAC, 70°C (158°F) 30K NC: 1/10 hp, 120 VAC (50,000 cycles)

Note: Only part numbers with the suffix “ASI” are TV-5 approved.

TÜV (VDE File No. R9151267)

Part number	Coil rating	Contact rating
G5LE	3, 5, 6, 9, 12, 24 VDC	1.2 A, 250 VAC (cosϕ = 0.4) 2.5 A, 250 VAC (resistive load) 5 A, 30 VDC (resistive load)
		2.5 A, 250 VAC (cosϕ = 0.4) 5 A, 250 VAC (resistive load) 8 A, 30 VDC (resistive load)

NOTE: DIMENSIONS SHOWN ARE IN MILLIMETERS. To convert millimeters to inches divide by 25.4.

OMRON®

OMRON ELECTRONICS, INC.
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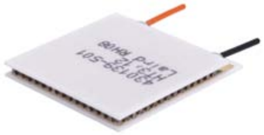
885 Milner Avenue
Scarborough, Ontario M1B 5V8
416-286-6465

Cat. No. GC RLY7 01/00 Specifications subject to change without notice. Printed in U.S.A.

ThermaTEC™ Series HT3-12-F2-3030

Thermoelectric Modules



The ThermaTEC™ Series of thermoelectric modules (TEMs) are designed to operate under cycling conditions or high temperature applications.

This product line is available in multiple configurations and is ideal for applications that require both heating and cooling mode (reverse polarity) or power generation. Assembled with proprietary solder construction, Bismuth Telluride semiconductor material and thermally conductive Aluminum Oxide ceramics, the ThermaTEC Series is designed for higher current and larger heat-pumping applications.

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Europe: +46.31.420530
Asia: +86.755.2714.1166
ets.sales@lairdtech.com
www.lairdtech.com

FEATURES

- Thermal cycling durability
- Power cycling reliability
- Precise temperature control
- Strong lead attachment
- RoHS compliant
- Continuous operation at high temperatures

APPLICATIONS

- Analytical instrumentation
- PCR cyclers
- Thermal test sockets
- Electronic enclosure cooling
- Chillers (liquid cooling)
- Power generation

SPECIFICATIONS

TECHNICAL		
Hot Side Temperature (°C)	25°C	50°C
Qmax (Watts)	24.7	27.2
Delta Tmax (°C)	63	75
Imax (Amps)	2.9	2.9
Vmax (Volts)	14.5	16.4
Module Resistance (Ohms)	4.65	5.24

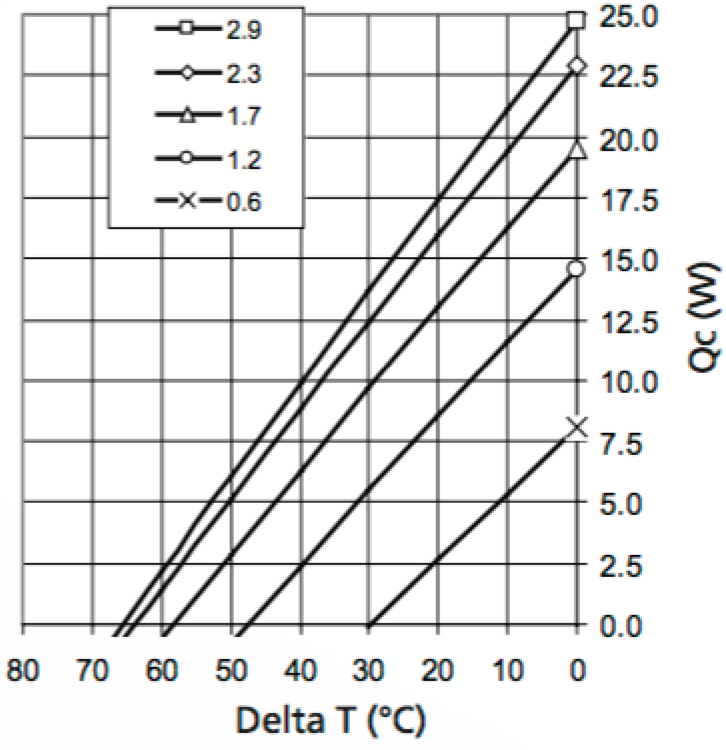
SUFFIX	THICKNESS (PRIOR TO TINNING)	FLATNESS & PARALLELISM	HOT FACE	COLD FACE	LEAD LENGTH
11	0.126”±0.005”	0.002” /0.0035”	Lapped	Lapped	6.0”
TA	0.126”±0.001”	0.001”/0.001”	Lapped	Lapped	6.0”
TB	0.126”±0.0005”	0.0005”/0.0005”	Lapped	Lapped	6.0”

SEALING OPTIONS

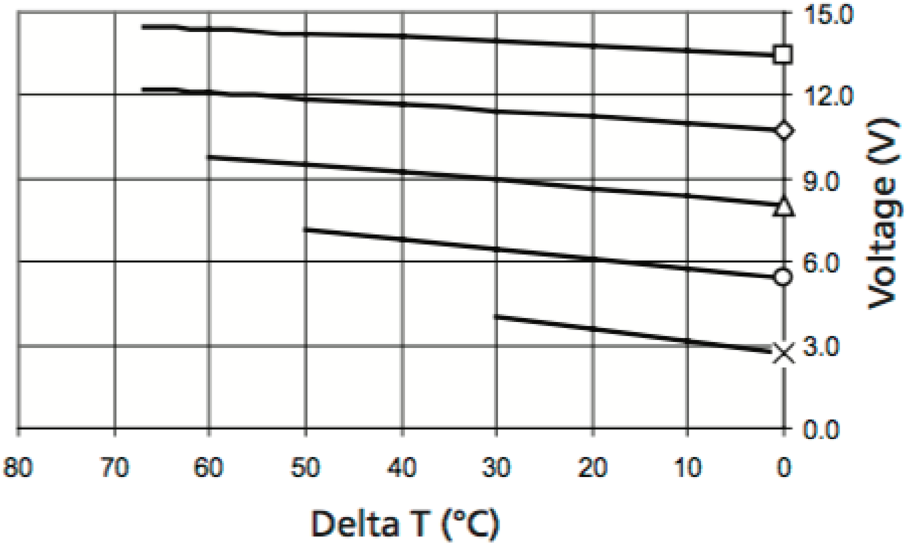
SUFFIX	SEALANT	COLOR	TEMP RANGE	DESCRIPTION
RT	RTV	White	-60 to 204 °C	Non-corrosive, silicone adhesive
EP	Epoxy	Black	-55 to 150 °C	Low density syntactic foam epoxy encapsulant

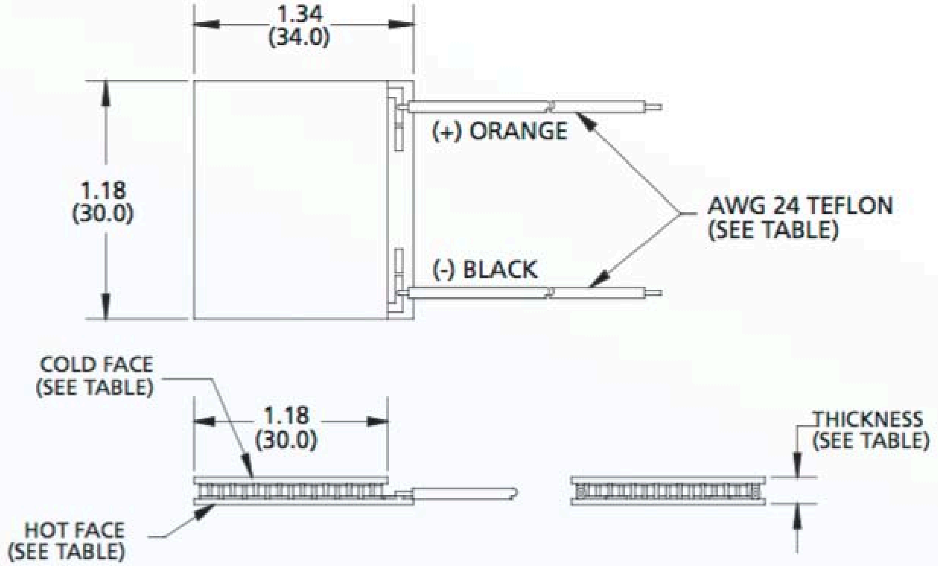
Performance Curves at Th =25°C

THERMO



ELECTRIC





Ceramic Material: Alumina (Al_2O_3)
Solder Construction: 271°C, Proprietary

NOTES

1. Max operating temperature: 175°C
2. Do not exceed Imax or Vmax when operating module
3. Reference assembly guidelines for recommended installation

LAIRD-ETS-HT3-12-F2-3030-DATA-SHEET-101416

Thermoelectric
HANDBOOK

Product Information
Assembly Information
Performance and Properties

www.lairdtech.com

Laird
TECHNOLOGIES®

Innovative **Technology**
for a **Connected** World

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Product Information

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Performance and Properties

Introduction to Thermoelectrics

Solid state heat pumps have been known since the discovery of the Peltier effect in 1834. The devices became commercially available in the 60's with the development of advanced semiconductor thermocouple materials in combination with ceramics substrates. Thermoelectric modules (TEMs) are solid-state heat pumps that require a heat exchanger to dissipate heat utilizing the Peltier Effect. During operation, DC current flows through the TEM to create heat transfer and a temperature differential across the ceramic surfaces, causing one side of the TEM to be cold, while the other side is hot. A standard single-stage TEM can achieve temperature differentials of up to 70°C. However, modern growth and processing methods of semiconductor materials are exceeding this limitation.

TEMs have several advantages over alternate cooling technologies. They have no moving parts, so the solid state construction results in high reliability. TEMs can cool devices down to well below ambient. Colder temperatures can be achieved, down to minus 100°C, by using a multistage thermoelectric module in a vacuum environment. Thermoelectrics are able to heat and cool by simply reversing the polarity, which changes the direction of heat transfer. This allows temperature control to be very precise, where up to ±0.01°C can be maintained under steady-state conditions. In heating mode TEMs are much more efficient than conventional resistant heaters because they generate heat from the input power supplied plus additional heat generated by the heat pumping action that occurs.

A typical TEM measures 30 mm x 30 mm x 3.6 mm. Their geometric footprints are small as they vary from 2 x 2 mm's to 62 x 62 mm's and are light in weight. This makes thermoelectrics ideal for applications with tight geometric space constraints or low weight requirements when compared too much larger cooling technologies, such as conventional compressor-based systems. TEMs can also be used as a power generator converting waste heat into energy as small DC power sources in remote locations.

When should you use thermoelectrics?

Thermoelectrics are ideal for applications that require active cooling to below ambient and have cooling capacity requirements of up to 600 Watts. A design engineer should consider them when the system design criteria includes such factors as precise temperature control, high reliability, compact geometry constraints, low weight and environmental requirements. These products are ideal for many of the consumer, food & beverage, medical, telecom, photonics and industrial applications requiring thermal management.

Thermoelectric Modules available from Laird Technologies

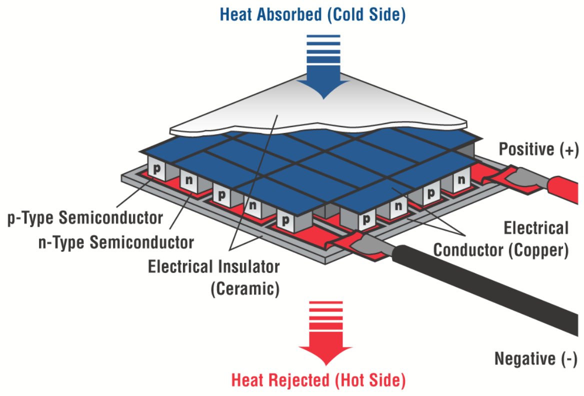
CP Series offer reliable cooling capacity in the range of 10 to 100 watts. They have a wide product breadth that is available in numerous heat pumping capacities, geometric shapes, and input power ranges. These modules are designed for higher current and larger heat pumping applications with a maximum operating temperature of 80°C.

OptoTEC™ Series have a geometric footprint less than 13x13 mm and are used in applications that have lower cooling requirements of less than 10 watts. These modules offer several surface finishing options, such as metallization or pre-tinning to allow for soldering between TEM and mating conduction surfaces.

MS Series offer the highest temperature differential, (ΔT). Each stage is stacked one on top of another, creating a multistage module. Available in numerous temperature differentials and geometric shapes, these modules are designed for lower heat pumping applications.

ThermaTEC™ Series are designed to operate in thermal cycling conditions that require reliable performance in both heating and cooling mode (reverse polarity). Thermal stresses generated in these applications will cause standard modules to fatigue over time. These modules are designed for higher current and higher heat pumping applications with a maximum operating temperature of 175°C

UltraTEC™ Series offer the highest heat pumping capacity within a surface area. Heat pumping densities of up to 14 W/cm^2, or twice as high as standard modules, can be achieved. The cooling capacity can range from 100 to 300 watts. TEMs are also ideal for applications that require low temperature differentials and high coefficient of performance (COP).



Structure and Function

Since thermoelectric cooling systems are most often compared to conventional systems, perhaps the best way to show the differences in the two refrigeration methods is to describe the systems themselves.

A conventional cooling system contains three fundamental parts - the evaporator, compressor and condenser. The evaporator or cold section is the part where the pressurized refrigerant is allowed to expand, boil and evaporate. During this change of state from liquid to gas, energy (heat) is absorbed. The compressor acts as the refrigerant pump and recompresses the gas to a liquid. The condenser expels the heat absorbed at the evaporator plus the heat produced during compression, into the environment or ambient.

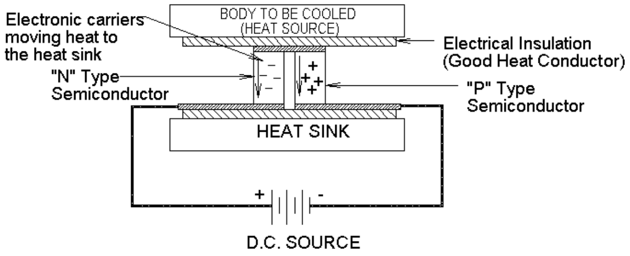
A thermoelectric has analogous parts. At the cold junction, energy (heat) is absorbed by electrons as they pass from a low energy level in the p-type semiconductor element, to a higher energy level in the n-type semiconductor element. The power supply provides the energy to move the electrons through the system. At the hot junction, energy is expelled to a heat sink as electrons move from a high energy level element (n-type) to a lower energy level element (p-type).

Thermoelectric Modules (TEMs) are heat pumps – solid state devices without moving parts, fluids or gasses. The basic laws of thermodynamics apply to these devices just as they do to conventional heat pumps, absorption refrigerators and other devices involving the transfer of heat energy.

An analogy often used to help comprehend a thermoelectric cooling system is that of a standard thermocouple used to measure temperature. Thermocouples of this type are made by connecting two wires of dissimilar metal, typically copper/constantan, in such a manner so that two junctions are formed. One junction is kept at some reference temperatures the other is attached to the control device measurement. The system is used when the circuit is opened at some point and the generated voltage is measured. Reversing this train of thought, imagine a pair of fixed junctions into which electrical energy is applied causing one junction to become cold while the other becomes hot.

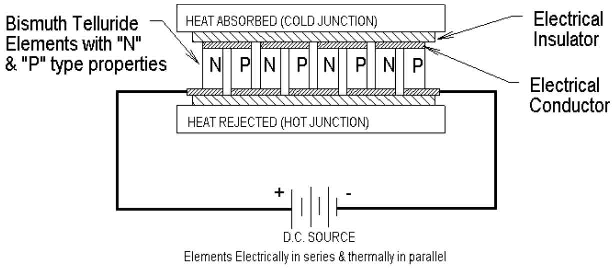
Thermoelectric cooling couples (Fig. 1) are made from two elements of semiconductor, primarily Bismuth Telluride, heavily doped to create either an excess (n-type) or deficiency (p-type) of electrons. Heat absorbed at the cold junction is pumped to the hot junction at a rate proportional to current passing through the circuit and the number of couples.

Figure 1: Cross Section of a typical TE Couple



In practical use, couples are combined in a module (Fig. 2) where they are connected electrically in series, and thermally in parallel. Normally a TEM is the smallest component commercially available.

Figure 2: Typical TE Module Assembly



TEMs are available in a great variety of sizes, shapes, operating currents, operating voltages and ranges of heat pumping capacity. The trend, however, is toward a larger number of couples operating at lower currents. The user can select the quantity, size or capacity of the module to fit the exact requirement without paying for excess power.

There is usually a "need" to use thermoelectrics instead of other forms of cooling. The "need" may be a special consideration of size, space, weight, efficiency, reliability or environmental conditions such as operating in a vacuum.

Once it has been decided that thermoelectrics are to be considered, the next task is to select the thermoelectric(s) that will satisfy the particular set of requirements. Three specific system parameters must be determined before device selection can begin.

These are:

- Tc Cold Surface Temperature
- Th Hot Surface Temperature
- Qc The amount of heat to be absorbed at the Cold Surface of the TEM

In most cases, the cold surface temperature is usually given as part of the problem – that is to say that some object(s) is to be cooled to some temperature. Generally, if the object to be cooled is in direct intimate contact with the cold surface of the thermoelectric, the desired temperature of the object can be considered the temperature of the cold surface of the TEM (Tc). There are situations where the object to be cooled is not in intimate contact with the cold surface of the TEM, such as volume cooling where a heat exchanger is required on the cold surface of the TEM. When this type of system is employed, the cold surface of the TEM (Tc) may need to be several degrees colder than the ultimate desired object temperature.

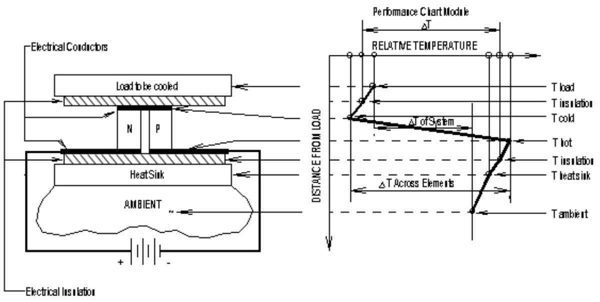
The Hot Surface Temperature is defined by two major parameters:

1) The temperature of the ambient environment to which the heat is being rejected.

2) The efficiency of the heat exchanger that is between the hot surface of the TEM and the ambient environment.

These two temperatures (Tc & Th) and the difference between them (ΔT) are very important parameters and therefore must be accurately determined if the design is to operate as desired. Figure 3 represents a typical temperature profile across a thermoelectric system.

Figure 3: Typical Temperature Relationship in a TEC



The third and often most difficult parameter to accurately quantify is the amount of heat to be removed or absorbed by the cold surface of the TEM, (Qc). All thermal loads to the TEM must be considered. These thermal loads include, but are not limited to, the active heat load (I^2R) from the electronic device to be cooled and passive heat load where heat loss can occur through any object in contact with ambient environment (i.e. electrical leads, insulation, air or gas surrounding objects, mechanical fasteners, etc.). In some cases radiant heat effects must also be considered.

Single stage thermoelectric modules are capable of producing a "no load" temperature differential of approximately 70°C. Temperature differentials greater than this can be achieved by stacking one thermoelectric on top of another. This practice is often referred to as Cascading. The design of a cascaded device is much more complex than that of a single stage device, and is beyond the scope of these notes. Should a cascaded device be required, design assistance can be provided by Laird Technologies Engineers.

Once the three basic parameters have been quantified, the selection process for a particular module or array of TEMs may begin. Some common heat transfer equations are attached for help in quantifying Qc & Th.

There are many different modules or sets of modules that could be used for any specific application. One additional criteria that is often used to pick the "best" module(s) is Coefficient of Performance (COP). COP is defined as the heat absorbed at the cold junction, divided by the input power (Qc / P). The maximum COP case has the advantages of minimum input power and therefore, minimum total heat to be rejected by the heat exchanger (Qh = Qc + P). These advantages come at a cost, which in this case is the additional or larger TEM required to operate at COP maximum. It naturally follows that the major advantage of the minimum COP case is the lowest initial cost.

Temperature Control

When designing a thermoelectric system power supplies, temperature controllers, and temperature sensors are components that also require careful consideration.

Thermoelectric devices require a DC power source to operate. The power supply output should be matched to the operational voltage of the thermoelectric modules and fans. Do not operate thermoelectric devices above the specified maximum voltage. Doing so will degrade the operational performance of the TEMs. The power supply should also have a small ripple voltage (maximum of 10% of full output). Ripple voltage is a fluctuation of the power supply output voltage and therefore is an AC component of the DC power source. AC power will degrade the operational performance of the TEMs. The degradation in performance due to ripple voltage can be approximated by:

$\Delta T / \Delta T_{max} = 1 / (1+N^2)$, where N is a percentage of current ripple, expressed as a decimal. ***Laird Technologies recommends no more than a 10% ripple***.

Temperature control can be accomplished by using one of two control methods: Open Loop (manual) and Closed Loop (automatic). In the Open Loop method, an operator adjusts the output of the power supply to achieve and maintain a steady temperature. In the Closed Loop method an electronic controller runs an algorithm that utilizes feedback data from sensors within the system to vary the output of the power supply to control the temperature.

Temperature controllers can have a single directional output or a bidirectional output. A temperature controller that has a single directional output can operate in Heating or Cooling mode. Controllers with a single directional output are used in maintaining a constant temperature within a system surrounded by a relatively constant ambient temperature (i.e. refrigeration or hot food storage). A temperature controller with a bidirectional output can operate in Heating and Cooling mode. Controllers with a bidirectional output are used for maintaining a constant temperature within a system surrounded by an ambient environment with large temperature fluctuations (i.e. back-up battery storage, climate control).

Temperature controllers can also have two regulation modes: thermostatic (On/Off) or proportional control. Thermostatic controllers operate by turning on the TEM in order to heat or cool to a set point. The set point temperature tolerance is defined by a hysteresis range. Once the set point is achieved the controller shuts off the TEM. When the control temperature changes to outside the hysteresis range the controller turns on power to the TEMs and restarts the cooling or heating mode process. This cycle continues until the controller is shut down. Thermostatic control is often used in climate control and refrigeration, where a narrow temperature swing can be tolerated.

Proportional controllers use proportional regulation to maintain a constant temperature with no swing in the control temperature. This is often accomplished by using a Proportional Integral Derivative (PID) algorithm to determine the output value and a Pulse Width Modulation (PWM) output to handle the physical control. When using a controller with a PWM output, a capacitor can be placed (electrically) across the output to filter the voltage to the TEM. Proportional controllers are often used in heating and cooling systems where the temperature must stay constant (with no change) regardless of the ambient temperature, such as liquid chiller systems used in medical diagnostics.

Regardless of the controller used, the easiest feedback parameter to detect and measure is temperature. The sensors most commonly used by temperature controllers are thermocouples, thermistors, and RTD's. Depending on the system; one or more temperature sensors may be used for the purpose of control. The temperature sensor feedback is compared by the controller to a set point or another temperature to determine the power supply output.
The temperature feedback sensor(s) will most likely be determined by the controller specified. Some controllers even include a sensor with purchase.

To begin selection of a TEM controller, consider the following questions:

1. What is the maximum voltage & current of TEM used in application? (also needed for selecting a power supply)
2. Does the system need to Heat, Cool or Heat & Cool?
3. Can the system tolerate a temperature swing of 3°C?

Once answered, the selection of the basic functions of a temperature controller can be identified. The controller selected needs to be capable of handling the maximum voltage and current to properly control the TEM and power fans.

If the answers to question 2 is "Heat" or "Cool" and the answer to question 3 is "Yes" then the required controller is single directional and thermostatic.

If the answers to question 2 is "Heat" or "Cool" and the answer to question 3 is "No" then the required controller is single directional and proportional.

If the answers to question 2 is "Heat & Cool" and the answer to question 3 is "Yes" then the required controller is bidirectional and thermostatic.

If the answers to question 2 is "Heat & Cool" and the answer to question 3 is "No" then the required controller is bidirectional and proportional.

TEM controllers also can accommodate more advanced options to trip alarms, control fan speeds and interface remotely with PC or UI, but these are beyond the scope of this handbook. However, some basic questions to consider for TEM controller designs are:

1. What alarms/indicators are required for User Interface?
2. Does the controller need to interface with a PC?
3. Does the TEM controller provide fan control?
4. Does the temperature set point need to be changed by the end user?

Other design considerations may exist and should be considered during system level design.

Laird Technologies offers a variety of Closed Loop Temperature Controllers. The controller offering includes single and bidirectional output controllers that employ thermistor temperature sensor feedback, fan controls, alarms, and a range of control algorithms ranging from thermostatic (ON/OFF) to PID. Laird Technologies also has the ability to customize and design temperature controllers to meet unique application requirements. Consult with a Laird Technologies Sales Engineer on available product offerings or customized solutions that may fit to your design criteria.

Parameters Required for Device Selection

There are certain minimum specifications that everyone must answer before the selection of a thermoelectric module (TEM) can begin. Specifically there are three parameters that are required. Two of these parameters are the temperatures that define the gradient across the TEM. The third parameter is the total amount of heat that must be pumped by the device.

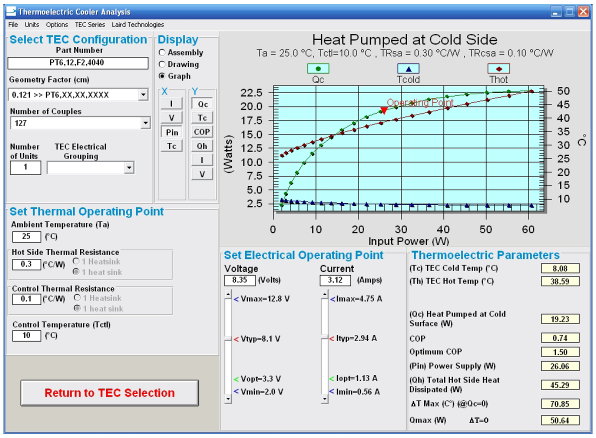
The temperature gradient across the TEM, actual ∆T is not the same as the apparent, system level ∆T. The difference between these two ∆Ts is often ignored, which results in an under-designed system. The magnitude of the difference in ∆Ts is largely dependent on the thermal resistance of the heat exchangers that are used on the hot or cold sides of the TEM.

Unfortunately, there are no "Hard Rules" that will accurately define these differences. Typical allowances for the hot side of a system are:

1. finned forced air: 10 to 15°C
2. free convection: 20 to 40°C
3. liquid exchangers: 2 to 5°C above liquid temperature

Since the heat flux densities on the cold side of the system are considerably lower than those on the hot side, an allowance of about 50% of the hot side figures (assuming similar types of heat exchangers) can be used. It is good practice, to check the outputs of the selection process to reassure that the heat sink design parameters are reasonable.

The third parameter that must be identified for the selection process, is the total heat to be pumped by the TEM. This is often the most difficult number to estimate. To reduce the temperature of an object, heat must be removed faster than heat enters it. There are generally two broad classifications of the heat that must be removed from the device. The first is the real, sensible or "active" heat load. This is the load that is representative of what wants to be done. This load could be the I^2R load of an electrical component, the load of dehumidifying air, or the load of cooling objects. The "other" kind of load is often referred to as the passive heat load. This is the load due to the fact that the object is cooler than the surrounding environment. This load can be composed of conduction and convection of the surrounding gas, "leak" through insulation, conduction through wires, condensation of water, and in some cases formation of ice. Regardless of the source of these passive loads, they must not be ignored.



Ta = 25.0 °C, Tctl=10.0 °C , TRsa = 0.30 °C/W , TRcsa = 0.10 °C/W

Part Number: PT6,12,F2,4040

Geometry Factor (cm): 0.121 >> PT6,XX,XX,XXXX

Number of Couples: 127

Number of Units: 1

TEC Electrical Grouping:

Ambient Temperature (Ta): 25 (°C)

Hot Side Thermal Resistance: 0.3 (°C/W) ○ 1 Heatsink ● 1 heat sink

Control Thermal Resistance: 0.1 (°C/W) ○ 1 Heatsink ● 1 heat sink

Control Temperature (Tctl): 10 (°C)

Voltage: 8.35 (Volts)

< Vmax=12.8 V
< Vtyp=8.1 V
< Vopt=3.3 V
< Vmin=2.0 V

Current: 3.12 (Amps)

< Imax=4.75 A
< Ityp=2.94 A
< Iopt=1.13 A
< Imin=0.56 A

(Tc) TEC Cold Temp (°C)	8.08
(Th) TEC Hot Temp (°C)	38.59
(Qc) Heat Pumped at Cold Surface (W)	19.23
COP	0.74
Optimum COP	1.50
(Pin) Power Supply (W)	26.06
(Qh) Total Hot Side Heat Dissipated (W)	45.29
∆T Max (C°) (@Qc=0)	70.85
Qmax (W) ∆T=0	50.64

There are other things that may be very important to a specific application, such as physical dimensions, input power limitations or cost. Even though these are important, they are only secondary. Laird Technologies' approach to thermoelectric module selection/recommendation utilizes a proprietary computer aided design program called AZTEC™ which selects an optimized thermoelectric design from a given set of parameters: hot side temperature, desired cold side temperature, and the total heat load to be pumped over the actual ∆T.

A checklist has been enclosed to assist with defining your application's existing conditions. If you should require any further assistance please contact one of Laird Technologies sales engineers.

Sealant Options

Most applications operate in a room temperature environment and cool to below dew point. As a result, moisture in the environment will condense onto the cold side heat exchanger and may accumulate around mounting hardware and eventually penetrate to the TEM. The presence of moisture will cause corrosion that will degrade the useful life of a thermoelectric. Two perimeter sealants are generally used because they provide moisture protection against condensation, have high dielectric strength and low thermal conductivity.

Silicone (RTV) is an all purpose sealant that exhibits good sealing characteristics and retains its elastomeric properties over a wide temperature range, -60 to 200°C. The sealant is non-corrosive to many chemicals and exhibits good electrical properties with low thermal conductivity. It is suitable for high volume applications for ease of use and is cost effective. However, over time it is impervious to vapor migration that can actually trap small amounts of moisture inside the TEM once the vapor condenses. This may or may not be a problem dependent on life expectancy of application and environmental conditions.

Epoxy (EP) is an effective barrier to moisture that exhibits a useable temperature range of -40 to 130°C. When cured the material is completely uni-cellular and therefore the moisture absorption is negligible. The material exhibits a low dielectric constant, low coefficient of thermal expansion and low shrinkage. Epoxies are ideal for applications requiring long life expectancies. However, applying epoxy onto TEM can be cumbersome as multiple fillers are required to be mixed and working life tends to be short, which makes it more difficult to automate for higher volume production runs.

It should be noted that since sealants come in contact with the top and bottom ceramic, they act as a thermal paths and transfer heat. The thermal conductivity of RTV and Epoxy is low, but it still can diminish the cooling performance of a TEM by up to 10%. However, it is necessary to specify for applications that maybe susceptible to condensation.

Thermoelectric Array

Wiring multiple TEMs together is commonly referred to as a TE array. The decision to wire TEMs in series or in parallel is primarily based on available input power requirements. No additional performance benefit will be achieved by wire arrangement. TE arrays are commonly used for higher heat pumping capacities and can be more efficient than a single TEM by taking advantage of dissipating heat over a larger surface area. When mounting a TE array onto a heat exchanger, the recommended lapping tolerances are ± 0.025 mm for two TEMs and ± 0.0125mm for three or more. This is done to maximize the thermal contact between the TEM and mating heat exchangers.

One advantage of wiring a TE array in parallel versus in series is that the entire TE array will not fail if one TEM has an open circuit. This can be beneficial for applications that require redundancy.

Design/Selection Checklist

The information requested below is vital to the design/selection of a thermoelectric device to achieve your desired performance.

Please attempt to define as many of your application's existing conditions and limiting factors as possible.
(Please indicate units on all parameters.)

I. Ambient Environment

Temperature = ____________________

☐ Air
☐ Vacuum
☐ Other

II. Cold Spot

Temperature: ______________
Size: ______________
Insulated? ___________Type:_____________Thickness: _____________
Desired Interface:

☐ Plate
☐ Fins
☐ Fluid Flow (parameters) ________________
☐ Other _______________

III. Heat Sink

☐ Finned - Free Convection
☐ Finned - Forced Convection
☐ Liquid Cooled

Maximum Heat Sink Temp. _________________ -or-Heat Sink Rating (°C/W) ___________________

IV. Heat Load at Cold Spot = ____________________

(if applicable, above should include:)
Active:
I^2R __________________
Passive:
Radiation= _________________
Convection= ________________
Insulation Losses= _________________
Conduction Losses= ________________(e.g. leads)
Transient Load= _________________(Mass - time)

V. Restrictions on Power Available (indicate most important)

☐ Current: _________________
☐ Voltage: __________________
☐ Power: __________________
☐ No Restrictions

VI. Restrictions on Size: ___________________

VII. To ensure the most effective response:

Please provide a rough, dimensioned sketch of the application, indicating the anticipated physical configuration and thermoelectric module placement.

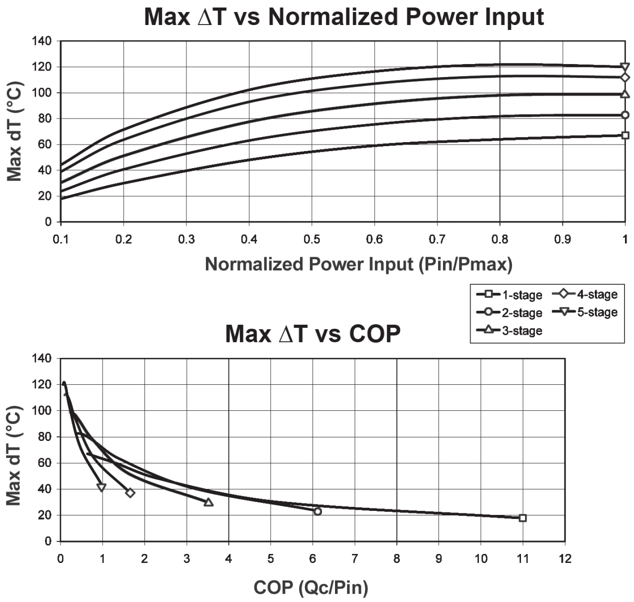
Please print this form and fill in the blanks
Telephone: 888 246-9050 Email: CLV-customerserivce@lairdtech.com

Thermoelectric Multistage (Cascade) Modules

A multistage thermoelectric module should be used only when a single stage module does not meet control temperature requirements. Figure 4 depicts two graphs: the first shows the ΔT vs. Normalized Power input (Pin/Pmax) of single and multistage modules. The second graphs shows the ΔT vs. COP. COP is defined as the amount of heat absorbed at the cold side of the TEM (in thermal watts) divided by the input power (in electrical watts).

These figures should help identify when to consider cascades since they portray the effective ΔT range of the various stages. A two-stage cascade should be considered somewhere between a ΔT of 40°C and 65°C. Below a ΔT of 40°C, a single stage module may be used, and a ΔT above 65°C may require a 3, 4 or even 5 stage module.

Figure 4: Multistage Temperature Differential Graphs



There is another very significant factor that must always be considered and that is cost. As the number of stages increase, so does the cost. Certain applications require a trade-off between COP and cost. As with any other thermoelectric system, to begin the selection process requires the definition of at least three parameters:

- Tc Cold Side Temperature
- Th Hot Side Temperature
- Qc The amount of heat to be removed (absorbed by the cooled surface of the TEM) (in watts)

Once ΔT (Th - Tc) and the heat load have been defined, utilization of Figure 4 will yield the number of stages that should be considered. Knowing COP and Qc , input power can also be estimated. The values listed in Figure 4 are theoretical maximums. Any device that is actually manufactured will rarely achieve these maximums, but should closely approach this value.

Laird Technologies offers a line of MS Series cascades though there are no standard applications. Each need for a cascade is unique, so too should be the device selected to fill the need. Laird Technologies has developed a proprietary computer aided design selection tool called Aztec™ to help select a device. The three parameters listed are used as inputs to the programs. Other variables such as physical size, and operating voltage or current can, within limits, be used to make the final selection. More than 40,000 different cascades can be assembled utilizing available ceramic patterns. This allows near custom design, at near "standard" prices. When the three parameters have been defined, please contact a Laird Technologies sales engineer for assistance in cascade selection.

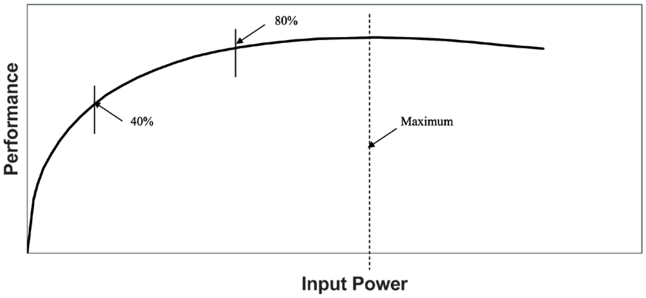
Typical Device Performance

When PERFORMANCE vs. INPUT POWER is plotted for any thermoelectric device, the resultant curve will appear as in figure 5 below. Performance can be ΔT (Th - Tc), heat pumped at the cold side (Qc), or as in most cases, a combination of these two parameters.

Input power can be current (I), voltage (V) or the product of IV. When we refer to the ΔTmax or Qc max, we are referring to that point where the curve peaks. The same is true when referring to either Imax or Vmax. Since operating at or very near the peak is relatively inefficient, most devices are operated somewhere between 40% and 80% of Input Power MAX.

As stated, devices are normally operated on the near-linear, upward sloping portion of the curve. When automatic or closed loop temperature control is being used, current or voltage limits should be set below the MAX intercepts.

Figure 5: Performance vs Input Power



Assembly Tips

The techniques used in the assembly of a thermoelectric system can be as important as the selection of the thermoelectric module (TEM). It is imperative to keep in mind the purpose of the assembly – namely to transfer heat. Generally a TEM, in cooling mode, moves heat from an object to ambient environment. All of the mechanical interfaces between the device to be cooled and ambient are also thermal interfaces. Similarly all thermal interfaces tend to inhibit the transfer of heat or add thermal resistance to system, which lowers COP. Again, when considering assembly techniques every reasonable effort should be made to minimize the thermal resistance between hot and cold surfaces.

Mechanical tolerances for heat exchanger surfaces should not exceed .025 mm/mm with a maximum of .076 mm total Indicated Reading. If it is necessary to use multiple TEMs in an array between common plates, then the height variation between modules should not exceed 0.025 mm (request tolerance lapped modules when placing order). Most thermoelectric assemblies (TEAs) utilize thermal interface materials, such as grease. The grease thickness should be kept to 0.025 ± .013 mm to minimize thermal resistance. A printer's ink roller and screen works well for maintaining grease thickness. When these types of tolerances are to be held, a certain level of cleanliness must be maintained to minimize contaminants.

Once the TEMs have been assembled between the heat exchangers, some form of insulation should be used between the exchangers surrounding the modules. Since the area within the module, (i.e. the element matrix), is an open DC circuit and a temperature gradient is present, air flow should be minimized to prevent condensation. Typically, a TEM is about 5.0 mm thick, so any insulation that can be provided will minimize heat loss between hot and cold side heat exchangers. The presence of the insulation/seal also offers protection from outside contaminants.

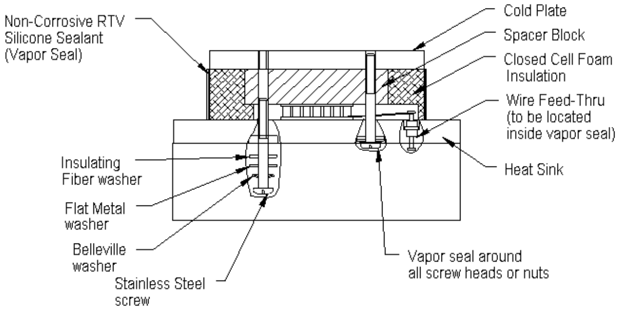
The insulation/seal is often most easily provided by inserting a die cut closed cell polyurethane foam around the cavity and sealing with either an RTV type substance or, for more physical integrity, an epoxy coat. Whatever form is used, it should provide the protection outlined above. It is often desirable to provide strain relief for the input lead wires to TEM, not only to protect the leads themselves, but to help maintain the integrity of the seal about the modules.

We have included an Assembly Tips drawing (Fig. 6). This drawing shows the details of the recommended construction of a typical assembly. The use of a "spacer block" yields maximum heat transfer, while separating the hottest and coldest parts of the system, by the maximum amount of insulation. The "spacer blocks" are used on the cold side of the system due to the lower heat flux density. In addition, the details of a feed thru and vapor sealing system that can be used for maximum protection from the environment are shown.

If you follow the recommendations shown in these drawings than you will see a significant improvement in performance. When testing an assembly of this type it is important to monitor temperature. Measuring temperature of the cooling fluids, inlet and outlet temperatures as well as flow rates is necessary. This is true if either gas or liquid fluids are used. Knowing input power to the TEM, both voltage and current, will also help in determining the cause of a potential problem.

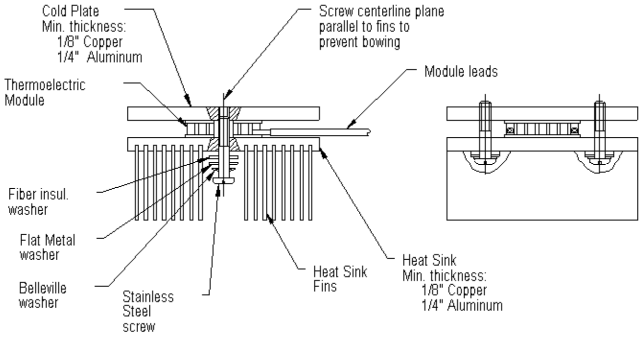
In addition we have enclosed step-by-step procedure for assembling Laird Technologies modules, Solderable or Lapped modules to heat-exchangers.

Figure 6: Assembly Tips Drawing



If you should require any further assistance, please contact one of our engineers. Our many years of experience in working with customers ensuring reliable and efficient application of our products has proven to be essential to product success.

Figure 7: Assembly Procedures Drawing



Procedure For Assembling Lapped Modules To Heat Exchangers

IMPORTANT: When two or more thermoelectric modules (TEMs) are mounted between a common heat exchanger base, the TEMs thickness tolerance should not vary more than ± 0.025 mm. Contact our sales engineer for more information on tolerance lapping requirements for TEMs in an array.

Step 1. Prepare cold plate and heat sink surfaces as follows:

A) Grind or lap flat to within +/- 0.025 mm in module area.

B) Locate mounting holes as close as possible to opposite edges of module (3.18 mm clearance recommended, 12.7 mm maximum), in the same plane line as the heat exchanger fins. This orientation utilizes the additional structural strength of the fins to prevent bowing. Drill clearance holes on one surface and drill and tap opposite surface accordingly (see sketch in Assembly Tips). If a spacer block is used to increase distance between surfaces, performance is greater if the spacer block is on the cold side of system.

C) Remove all burrs, chips and foreign matter from thermoelectric module mounting area.

Step 2. Thoroughly clean and degrease thermoelectric module, heat exchanger and cold surface.

Step 3. Apply a thin continuous film of thermal grease (Laird Technologies grease type 1500) to module hot side surface and to module area on heat exchanger.

Step 4. Locate module on heat exchanger, hot side down.

Step 5. Gently oscillate module back and forth, exerting uniform downward pressure, noting efflux of thermal compound around edges of module. Continue motion until resistance is felt.

Step 6. Repeat Step #3 for cold side surface and cold plate.

Step 7. Position cold plate on module.

Step 8. Repeat Step #5, sliding cold plate instead of module. Be particularly careful to maintain uniform pressure. Keep the module centered between the screws, or uneven compression will result.

Step 9. Before bolting, best results are obtained by preloading in compression the cold plate/heat exchanger/module assembly, applying a light load in line with center of module, using clamp or weights. For two-module assemblies, use three screws located on module center line, with middle screw located between modules. To preload, torque middle screw first. Bolt carefully, by applying torque in small increments, alternating between screws. Use a torque limiting screw driver. The recommended compression for a thermoelectric assembly is 10 to 21 kilograms per square centimeter (150 - 300 PSI) of module surface area. Using the following equation you can solve for torque per screw:

$$T = (C \times D \times P \times m^2) / (\text{\# of screws})$$

T = torque per screw (N-m)

C = torque coefficient (0.20 as received, 0.15 lubricated)

D = nominal screw size (M3 = 0.003, M4 = 0.004, M5 = 0.005)

P = Force (N-m^2)

m^2 = Module surface area (length x width)

Check torque after one hour and retighten if necessary.

Use Stainless Steel Screws, fiber insulating shoulder washers, and steel spring (Belleville or split lock type) washers (see sketch in Assembly Tips).

CAUTION

1. To ensure good thermal grease performance, there should be no bowing of either surface due to torquing. To prevent bowing, apply less torque if one or both surfaces are less than 3.18 mm thick copper or 6.35 mm thick aluminum.
2. Lead wires are soldered to module tabs with bismuth/tin solder (138°C). If lead wire replacement is necessary, use bismuth/tin solder.

DO NOT use lead / tin solder (180°C) to replace leads.

Procedure For Assembling Solderable Modules To Heat Exchangers

Step 1. Prepare cold plate and heat sink surfaces by drilling clearance holes on one surface, and drill and tap opposite accordingly (see sketch in Assembly Tips). If a spacer block is used to increase distance between surfaces, performance is greater if the spacer block is on cold side of system.

Step 2. Grind or lap flat cold plate (within +/- 0.025 mm) in module area. Thoroughly clean and degrease thermoelectric module, heat sink, and cold surface.

Step 3. Heat sink surface must be solderable (either copper or copper plated aluminum). Clean module area of heat sink surface by light abrasion and degrease thoroughly. Pretin with indium-tin eutectic type solder and flux.

Step 4. Module surface should be degreased and fluxed lightly. Heat pretinned and cleaned heat sink surface to 120 to 130°C (250 to 265°F). The module should not go above 138°C or the internal solder will reflow. Place module in position on surface, wait a few seconds for solder on module to melt and excess flux to boil out. When all solder is molten, module will have tendency to float on solder. Light swishing of module will enhance wetting.

- Note: If after all solder is molten there is a slight dragging effect on the module, a deficiency of solder is indicated. Remove module and add additional solder to heat exchange surface. Cool unit and solidify solder. If more than one module is used in the assembly, the flattened cold side surfaces of the module must be kept in a common plane during the soldering operation (Step #3). This can best be accomplished by first fastening the modules, cold face down and in proper array, to a ground flat plate of metal or graphite with double-faced tape. This assembly of modules and flat plate facilitates soldering of the modules to the heat sink, while ensuring that all module cold surfaces are maintained in a common plane and properly arrayed.

Step 5. After assembly cools, rinse thoroughly to remove all traces of flux residue.

Step 6. Assembly is now ready for bolting to cold plate. Apply a thin continuous film of thermal grease (Laird Technologies grease type 1500) to module top surface and to module area on cold plate and mate surfaces. Gently oscillate module back and forth, exerting uniform downward pressure, noting efflux of thermal compound around edges of module. Continue motion until resistance is felt.

Step 7. Before bolting, best results are obtained by preloading in compression the cold plate/heat exchanger/module assembly, applying a light load in line with center of module, using clamp or weights. For two-module assemblies, use three screws located on module center line, with middle screw located between modules. To preload, torque middle screw first. Bolt carefully, by applying torque in small increments, alternating between screws. Use a torque limiting screw driver. The recommended compression for a TE assembly is 10 to 21 kilograms per square centimeter (150 - 300 PSI) of module surface area. Using the following equation we can solve for torque per screw:

$$T = (C \times D \times P \times m^2) / (\text{\# of screws})$$

T = torque per screw (N-m)
C = torque coefficient (0.20 as received, 0.15 lubricated)
D = nominal screw size (M3 = 0.003, M4 = 0.004, M5 = 0.005)

P = Force (N- m^2)
m^2 = Module surface area (length x width)

Check torque after one hour and retighten if necessary. **Use Stainless Steel Screws, fiber insulating shoulder washers, and steel spring (Belleville or split lock type) washers (see sketch in Assembly Tips).**

CAUTION

1. To ensure good thermal grease interfaces, there should be no bowing of either surface due to torquing. To prevent bowing, apply less torque if one or both surfaces are less than 3.18 mm thick copper or 6.35 mm thick aluminum.

2. Lead wires are soldered to module tabs with bismuth/tin solder (136°C). If lead wire replacement is necessary, use bismuth/tin solder.

DO NOT use lead / tin solder (180°C) to replace leads.

Device Performance Formulae

Heat Pumped at Cold Surface:	$Q_C = 2N [\alpha I T_C - ((I^2 \rho) / (2 G)) - \kappa \Delta T G]$
Voltage:	$V = 2N [((I \rho) / G) + (\alpha \Delta T)]$
Maximum Current:	$I_{max} = (\kappa G / \alpha) [(1 + (2 Z T_H)]^{1/2} - 1]$
Optimum Current:	$I_{opt} = [\kappa \Delta T G (1 + (1 + Z T_{ave})^{1/2})] / (\alpha T_{ave})$
Optimum COP (calculated at I_{opt}):	$COP_{opt} = (T_{ave} / \Delta T) [((1 + Z T_{ave})1/2 - 1) / ((1 + Z T_{ave})^{1/2} + 1)] - 1/2$
Maximum ΔT with Q = 0	$\Delta T_{max} = Th - [(1 + 2 Z T_H)^{1/2} - 1) / Z]$

Notation Definition

T_H	Hot Side Temperature (Kelvin)
T_C	Cold Side Temperature (Kelvin)
ΔT	$T_H - T_C$ (Kelvin)
T_{ave}	$1/2 (T_H + T_C)$ (Kelvin)
G	Area / Length of T.E. Element (cm)
N	Number of Thermocouples
I	Current (amps)
COP	Coefficient of Performance (Q_C / IV)
α	Seebeck Coefficient (volts / Kelvin)
ρ	Resistivity (Ω cm)
κ	Thermal Conductivity (watt / (cm Kelvin))
Z	Figure of Merit ($\alpha^2 / (\rho \kappa)$) (Kelvin^{-1})
S	Device Seebeck Voltage (2 α N) (volts / Kelvin)
R	Device Electrical Resistance (2 ρ N / G) (ohms)
K	Device Thermal Conductance (2 κ N G) (Watt / Kelvin)

Geometry Factor (G)

TEM				G	TEM				G
OT	08	-xx-	05	0.016	CP	5	-xx-	10	0.778
OT	12	-xx-	06	0.024	CP	5	-xx-	06	1.196
OT	15	-xx-	05	0.030	PT	2	-12-	30	0.046
OT	20	-xx-	04	0.040	PT	3	-12-	30	0.057
CP	08	-xx-	06	0.042	PT	4	-12-	30	0.079
CP	08	-xx-	05	0.052	PT	4	-7-	30	0.076
CP	10	-xx-	08	0.050	PT	4	-12-	40	0.076
CP	10	-xx-	06	0.061	PT	6	-xx-	xx	0.121
CP	10	-xx-	05	0.079	PT	8	-xx-	xx	0.171
CP	14	-xx-	10	0.077	HT	2	-12-	30	0.046
CP	14	-xx-	06	0.118	HT	3	-12-	30	0.057
CP	14	-xx-	045	0.171	HT	4	-12-	30	0.079
CP	20	-xx-	10	0.184	HT	4	-7-	30	0.076
CP	20	-xx-	06	0.282	HT	4	-12-	40	0.076
CP	28	-xx-	06	0.473	HT	6	-xx-	xx	0.121

Typical Material Parameters

T (Kelvin)	ρ	κ	Z
273	9.2×10^{-4}	1.61×10^{-2}	2.54×10^{-3}
300	1.01×10^{-3}	1.51×10^{-2}	2.68×10^{-3}
325	1.15×10^{-3}	1.53×10^{-2}	2.44×10^{-3}
350	1.28×10^{-3}	1.55×10^{-2}	2.22×10^{-3}
375	1.37×10^{-3}	1.58×10^{-2}	1.85×10^{-3}
400	1.48×10^{-3}	1.63×10^{-2}	1.59×10^{-3}
425	1.58×10^{-3}	1.73×10^{-2}	1.32×10^{-3}
450	1.68×10^{-3}	1.88×10^{-2}	1.08×10^{-3}
475	1.76×10^{-3}	2.09×10^{-2}	8.7×10^{-4}

These tables and attributes are also available on AZTEC™ thermoelectric module selection software

Heat Transfer Formulae

NOTE: Due to the relatively complex nature of heat transfer, results gained from application of these formulae, while useful, must be treated as approximations only. Design safety margins should be considered before final selection of any device.

1) Heat gained or lost through the walls of an insulated container:

$$\mathbf{Q = (A \times \Delta T \times K) / (\Delta X)}$$

Where:

Q = Heat (Watts)
A = External surface area of container (m^2)
ΔT = Temp. difference (inside vs. outside of container) (Kelvin)
K = Thermal conductivity of insulation (Watt / meter Kelvin)
ΔX = Insulation thickness (m)

2) Time required to change the temperature of an object:

$$\mathbf{t = (m \times Cp \times \Delta T) / Q}$$

Where:

t = Time interval (seconds)
m = Weight of the object (kg)
C_p = Specific heat of material (J / (kg K))
ΔT = Temperature change of object (Kelvin)
Q = Heat added or removed (Watts)

NOTE: It should be remembered that thermoelectric devices do not add or remove heat at a constant rate when ΔT is changing. An approximation for average Q is:

$$\mathbf{Qave = (Q\,(\Delta Tmax) + Q\,(\Delta Tmin)) / 2}$$

3) Heat transferred to or from a surface by convection:

$$\mathbf{Q = h \times A \times \Delta T}$$

Where:

Q = Heat (Watts)
h = Heat transfer coefficient (W / (m^2 K))
(1 to 30 = "Free" convection - gases, 10 to 100 = "Forced" convection - gases)
A = Exposed surface area (m^2)
ΔT = Surface Temperature - Ambient (Kelvin)

Conversions:

Thermal Conductivity	1 BTU / hr ft °F = 1.73 W / m K 1 W / m K = 0.578 BTU / hr ft °F	**Specific Heat**	1 BTU / lb °F = 4184 J / kg K 1 J / kg K = 2.39 x 10-4 BTU / lb °F
Power (heat flow rate)	1 W = 3.412 BTU / hr 1 BTU / hr = 0.293 W	**Heat Transfer Coefficient**	1 BTU / hr ft^2 °F = 5.677 W / m^2 °K 1 W / m^2 °K = 0.176 BTU / hr ft^2 °F
Area	1 ft^2 = 0.093 m^2 1 m^2 = 10.76 ft^2	**Mass**	1 lb = 0.4536 kg 1 kg = 2.205 lb
Length	1 ft = 0.305 m 1 m = 3.28 ft		

Typical Properties of Materials (@ 21°C)

Material Name	Density kg/m³	Thermal Conductivity W/m-K	Specific Heat J/kg-K	Thermal Expansion Coefficient x 10⁻⁶ cm/cm/°C
Air	1.2	0.026	1004	–
Alumina Ceramic-96%	3570	35.3	837	6.5
Aluminum Nitride Ceramic	3300	170-230	920	4.5
Aluminum	2710	204	900	22.5
Argon (Gas)	1.66	0.016	518	–
Bakelite	1280	0.23	1590	22.0
Beryllia Ceramic-99%	2880	230	1088	5.9
Bismuth Telluride	7530	1.5	544	13.0
Brass	8490	111	343	18.0
Bronze	8150	64	435	18.0
Concrete	2880	1.09	653	14.4
Constantan	8390	22.5	410	16.9
Copper	8960	386	385	16.7
Copper Tungsten	15650	180-200	385	6.5
Diamond 3	500	2300	509	–
Ethylene Glycol	1116	0.242	2385	–
Glass (Common)	2580	0.80	795	7
Glass Wool	200	0.040	670	–
Gold 1	9320	310	126	14.2
Graphite	1625	25-470	770	4.7
Iron (Cast)	7210	83	460	10.4
Kovar	8360	16.6	460	5.0
Lead	11210	35	130	29.3
Molybdenum	10240	142	251	4.9
Nickel	8910	90	448	11.9
Nitrogen (Gas)	1.14	0.026	1046	–
Platinum	21450	70.9	133	9.0
Plexiglass (Acrylic)	1410	0.26	1448	74
Polyurethane Foam	29	0.035	1130	–
Rubber	960	0.16	2009	72
Silicone (Undoped)	2330	144	712	–
Silver	10500	430	235	–
Solder (Tin/Lead)	9290	48	167	24.1
Stainless Steel	8010 1	3.8	460	17.1
Steel (Low Carbon)	7850	48	460	11.5
Styrofoam	29-56	.029	1.22	–
Teflon	2200	0.35	–	–
Thermal Grease	2400	0.87	2093	–
Tin	7310	64	226	23.4
Titanium	4372	20.7	460	8.2
Water (@ 70°F)	1000	0.61	4186	–
Wood (Oak)	610	0.15	2386	4.9
Wood (Pine)	510	0.11	2805	5.4
Zinc	7150	112	381 3	2.4

Reliability & Mean Time Between Failures (MTBF)

Thermoelectric devices are highly reliable due to their solid state construction. Although reliability is application dependent, MTBFs calculated as a result of tests performed by various customers are on the order of 200,000 hours at room temperature. Elevated temperature (80°C) MTBFs are conservatively reported to be on the order of 100,000 hours. Field experience by hundreds of customers representing more than 7,500,000 of our CP type modules and more than 800,000 OptoTEC™ type modules during the last ten years have resulted in a failure return of less than 0.1%. More than 90% of all modules returned were found to be failures resulting from mechanical abuse or overheating on the part of the customer. Thus, less than one failure per 10,000 modules used in systems could be suspect of product defect. Therefore, the combination of proper handling, and proper assembly techniques will yield an extremely reliable system.

Historical failure analysis has generally shown the cause of failure as one of two types: Mechanical damage as a result of improper handling or system assembly techniques.

Moisture:

Moisture must not penetrate into the thermoelectric module area. The presence of moisture will cause an electro-corrosion that will degrade the thermoelectric material, conductors and solders. Moisture can also provide an electrical path to ground causing an electrical short or hot side to cold side thermal short. A proper sealing method or dry atmosphere can eliminate these problems.

Shock and Vibration:

Thermoelectric modules in various types of assemblies have for years been used in different Military/Aerospace applications. Thermoelectric devices have been successfully subjected to shock and vibration requirements for aircraft, ordinance, space vehicles, shipboard use and most other such systems. While a thermoelectric device is quite strong in both tension and compression, it tends to be relatively weak in shear. When in a severe shock or vibration environment, care should be taken in the design of the assembly to ensure "compressive loading" of thermoelectric modules.

Mechanical Mounting:

A common failure mode during assembly of a thermoelectric module is un-even loading induced by improper torqing, bolting patterns, and mechanical conditions of heat exchangers. The polycrystalline thermoelectric material exhibits less strength perpendicular to the length (growth axis) than the horizontal axis. Thus, the thermoelectric elements are quite strong in compressive strength and tend to be weak in the shear direction. During assembly, un-even torquing or un-flat heat exchangers can cause severe shear forces. (See assembly instructions for proper mounting techniques.)

Inadvertent Overheating of the Module:

The direct soldering process does result in temperature restriction for operation or storage of the modules.

At temperatures above 80°C two phenomena seriously reduce useful life:

Above 80°C copper diffusion into the thermoelements occurs due to increasing solid solubility in the thermoelectric material and increasing diffusion rate. At 100 - 110°C the combined solubility and diffusion rate could result in approximately 25% loss of device performance within 100 hours.

Above 85°C in the soldering process (using Bismuth-Tin Alloy) small amounts of selenium, tellurium, antimony and nickel are inherently dissolved into the bismuth-tin solder. Although the melting point of the base solder is 136°C, the combined mixture of all elements results in either a minute eutectic phase or a highly effective solid state reaction occurring at above 85°C that starts to delaminate the ends of the thermoelements by physical penetration between cleavage planes in the thermoelectric material. This results in a mechanical failure of the interface.

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