Low Power, Programmable Temperature Controller

TMP01*

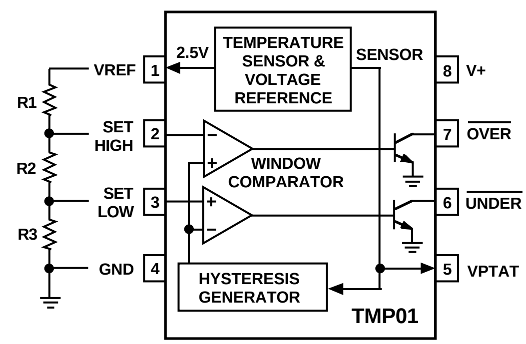
FEATURES

- –55°C to +125°C (–67°F to +257°F) Operation
- ±1.0°C Accuracy Over Temperature (typ)
- Temperature-Proportional Voltage Output
- User Programmable Temperature Trip Points
- User Programmable Hysteresis
- 20 mA Open Collector Trip Point Outputs
- TTL/CMOS Compatible
- Single-Supply Operation (4.5 V to 13.2 V)
- Low Cost 8-Pin DIP and SO Packages

APPLICATIONS

- Over/Under Temperature Sensor and Alarm
- Board Level Temperature Sensing
- Temperature Controllers
- Electronic Thermostats
- Thermal Protection
- HVAC Systems
- Industrial Process Control
- Remote Sensors

FUNCTIONAL BLOCK DIAGRAM



GENERAL DESCRIPTION

The TMP01 is a temperature sensor which generates a voltage output proportional to absolute temperature and a control signal from one of two outputs when the device is either above or below a specific temperature range. Both the high/low temperature trip points and hysteresis (overshoot) band are determined by user-selected external resistors. For high volume production, these resistors are available on-board.

The TMP01 consists of a bandgap voltage reference combined with a pair of matched comparators. The reference provides both a constant 2.5 V output and a voltage proportional to absolute temperature (VPTAT) which has a precise temperature coefficient of 5 mV/K and is 1.49 V (nominal) at +25°C. The comparators compare VPTAT with the externally set temperature trip points and generate an open-collector output signal when one of their respective thresholds has been exceeded.

Hysteresis is also programmed by the external resistor chain and is determined by the total current drawn out of the 2.5 V reference. This current is mirrored and used to generate a hysteresis offset voltage of the appropriate polarity after a comparator has been tripped. The comparators are connected in parallel, which guarantees that there is no hysteresis overlap and eliminates erratic transitions between adjacent trip zones.

The TMP01 utilizes proprietary thin-film resistors in conjunction with production laser trimming to maintain a temperature accuracy of ±1°C (typ) over the rated temperature range, with excellent linearity. The open-collector outputs are capable of sinking 20 mA, enabling the TMP01 to drive control relays directly. Operating from a +5 V supply, quiescent current is only 500 μA (max).

The TMP01 is available in the low cost 8-pin epoxy mini-DIP and SO (small outline) packages, and in die form.

*Protected by U.S. Patent No. 5,195,827.

REV. C

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TMP01EP/FP, TMP01ES/FS–SPECIFICATIONS Plastic DIP and Surface Mount Packages

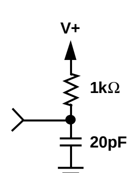
(V+ = +5 V, GND = 0 V, –40°C ≤ T_A ≤ +85°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
INPUTS SET HIGH, SET LOW						
Offset Voltage	V_{OS}			0.25		mV
Offset Voltage Drift	TCV_{OS}			3		µV/°C
Input Bias Current, "E"	I_B			25	50	nA
Input Bias Current, "F"	I_B			25	100	nA
OUTPUT VPTAT[1]						
Output Voltage	VPTAT	T_A = +25°C, No Load		1.49		V
Scale Factor	TC_{VPTAT}			5		mV/K
Temperature Accuracy, "E"		T_A = +25°C, No Load	–1.5	±0.5	1.5	°C
Temperature Accuracy, "F"		T_A = +25°C, No Load	–3	±1.0	3	°C
Temperature Accuracy, "E"		10°C < T_A < 40°C, No Load		±0.75		°C
Temperature Accuracy, "F"		10°C < T_A < 40°C, No Load		±1.5		°C
Temperature Accuracy, "E"		–40°C < T_A < 85°C, No Load	–3.0	±1	3.0	°C
Temperature Accuracy, "F"		–40°C < T_A < 85°C, No Load	–5.0	±2	5.0	°C
Temperature Accuracy, "E"		–55°C < T_A < 125°C, No Load		±1.5		°C
Temperature Accuracy, "F"		–55°C < T_A < 125°C, No Load		±2.5		°C
Repeatability Error	ΔVPTAT	Note 4		0.25		Degree
Long Term Drift Error		Notes 2 and 6		0.25	0.5	Degree
Power Supply Rejection Ratio	PSRR	T_A = +25°C, 4.5 V ≤ V+ ≤ 13.2 V		±0.02	±0.1	%/V
OUTPUT VREF						
Output Voltage, "E"	VREF	T_A = +25°C, No Load	2.495	2.500	2.505	V
Output Voltage, "F"	VREF	T_A = +25°C, No Load	2.490	2.500	2.510	V
Output Voltage, "E"	VREF	–40°C < T_A < 85°C, No Load	2.490	2.500	2.510	V
Output Voltage, "F"	VREF	–40°C < T_A < 85°C, No Load	2.485	2.500	2.515	V
Output Voltage, "E"	VREF	–55°C < T_A < 125°C, No Load		2.5 ± 0.01		V
Output Voltage, "F"	VREF	–55°C < T_A < 125°C, No Load		2.5 ± 0.015		V
Drift	TC_{VREF}			–10		ppm/°C
Line Regulation		4.5 V ≤ V+ ≤ 13.2 V		±0.01	±0.05	%/V
Load Regulation		10 µA ≤ I_{VREF} ≤ 500 µA		±0.1	±0.25	%/mA
Output Current, Zero Hysteresis	I_{VREF}			7		µA
Hysteresis Current Scale Factor	SF_{HYS}	(Note 1)		5.0		µA/°C
Turn-On Settling Time		To Rated Accuracy		25		µs
OPEN-COLLECTOR OUTPUTS OVER, UNDER						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA		0.25	0.4	V
Output Low Voltage	V_{OL}	I_{SINK} = 20 mA		0.6		V
Output Leakage Current	I_{OH}	V+ = 12 V		1	100	µA
Fall Time	t_{HL}	See Test Load		40		ns
POWER SUPPLY						
Supply Range	V+		4.5		13.2	V
Supply Current	I_{SY}	Unloaded, +V = 5 V		400	500	µA
Supply Current	I_{SY}	Unloaded, +V = 13.2 V		450	800	µA
Power Dissipation	P_{DISS}	+V = 5 V		2.0	2.5	mW

NOTES
[1]K = °C + 273.15.
[2]Guaranteed but not tested.
[3]Does not consider errors caused by heating due to dissipation of output load currents.
[4]Maximum deviation between +25°C readings after temperature cycling between –55°C and +125°C.
[5]Typical values indicate performance measured at T_A = +25°C.
[6]Observed in a group sample over an accelerated life test of 500 hours at 150°C.

Specifications subject to change without notice.

Test Load



TMP01FJ–SPECIFICATIONS

TO-99 Metal Can Package (V+ = +5 V, GND = 0 V, –40°C ≤ T_A ≤ +85°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
INPUTS SET HIGH, SET LOW						
Offset Voltage	V_{OS}			0.25		mV
Offset Voltage Drift	TCV_{OS}			3		µV/°C
Input Bias Current, "F"	I_B			25	100	nA
OUTPUT VPTAT[1]						
Output Voltage	VPTAT	T_A = +25°C, No Load		1.49		V
Scale Factor	TC_{VPTAT}			5		mV/K
Temperature Accuracy, "F"		T_A = +25°C, No Load	–3	±1.0	3	°C
Temperature Accuracy, "F"		10°C < T_A < 40°C, No Load		±1.5		°C
Temperature Accuracy, "F"		–40°C < T_A < 85°C, No Load	–5.0	±2	5.0	°C
Temperature Accuracy, "F"		–55°C < T_A < 125°C, No Load		±2.5		°C
Repeatability Error	ΔVPTAT	Note 4		0.25		Degree
Long Term Drift Error		Notes 2 and 6		0.25	0.5	Degree
Power Supply Rejection Ratio	PSRR	T_A = +25°C, 4.5 V ≤ V+ ≤ 13.2 V		±0.02	±0.1	%/V
OUTPUT VREF						
Output Voltage, "F"	VREF	T_A = +25°C, No Load	2.490	2.500	2.510	V
Output Voltage, "F"	VREF	–40°C < T_A < 85°C, No Load	2.480	2.500	2.520	V
Output Voltage, "F"	VREF	–55°C < T_A < 125°C, No Load		2.5 ± 0.015		V
Drift	TC_{VREF}			–10		ppm/°C
Line Regulation		4.5 V ≤ V+ ≤ 13.2 V		±0.01	±0.05	%/V
Load Regulation		10 µA ≤ I_{VREF} ≤ 500 µA		±0.1	±0.25	%/mA
Output Current, Zero Hysteresis	I_{VREF}			7		µA
Hysteresis Current Scale Factor	SF_{HYS}	(Note 1)		5.0		µA/°C
Turn-On Settling Time		To Rated Accuracy		25		µs
OPEN-COLLECTOR OUTPUTS OVER, UNDER						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA		0.25	0.4	V
Output Low Voltage	V_{OL}	I_{SINK} = 20 mA		0.6		V
Output Leakage Current	I_{OH}	V+ = 12 V		1	100	µA
Fall Time	t_{HL}	See Test Load, Note 2		40		ns
POWER SUPPLY						
Supply Range	V+		4.5		13.2	V
Supply Current	I_{SY}	Unloaded, +V = 5 V		400	500	µA
Supply Current	I_{SY}	Unloaded, +V = 13.2 V		450	800	µA
Power Dissipation	P_{DISS}	+V = 5 V		2.0	2.5	mW

NOTES
1. K = °C + 273.15.
2. Guaranteed but not tested.
3. Does not consider errors caused by heating due to dissipation of output load currents.
4. Maximum deviation between +25°C readings after temperature cycling between –55°C and +125°C.
5. Typical values indicate performance measured at T_A = +25°C.
6. Observed in a group sample over an accelerated life test of 500 hours at 150°C.

Specifications subject to change without notice.

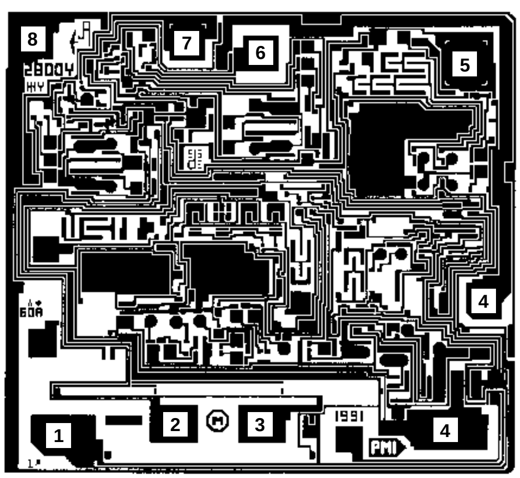
WAFER TEST LIMITS (V_{DD} = +5.0 V, GND = 0 V, T_A = +25°C, unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
INPUTS SET HIGH, SET LOW						
Input Bias Current	I_B				100	nA
OUTPUT VPTAT						
Temperature Accuracy		T_A = +25°C, No Load			1.5	°C
OUTPUT VREF						
Nominal Value	VREF	T_A = +25°C, No Load	2.490		2.510	V
Line Regulation		4.5 V ≤ V+ ≤ 13.2 V			±0.05	%/V
Load Regulation		10 μA ≤ I_{VREF} ≤ 500 μA			±0.25	%/mA
OPEN-COLLECTOR OUTPUTS OVER, UNDER						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA			0.4	mV
Output Low Voltage	V_{OL}	I_{SINK} = 20 mA			1.0	V
Output Leakage Current	I_{OH}				100	μA
POWER SUPPLY						
Supply Range	V+		4.5		13.2	V
Supply Current	I_{SY}	Unloaded			600	μA

NOTES
Electrical tests are performed at wafer probe to the limits shown. Due to variations in assembly methods and normal yield loss, yield after packaging is not guaranteed for standard product dice. Consult factory to negotiate specifications based on dice lot qualification through sample lot assembly and testing.

DICE CHARACTERISTICS

Die Size 0.078 × 0.071 inch, 5,538 sq. mils
(1.98 × 1.80 mm, 3.57 sq. mm)
Transistor Count: 105



1. VREF
2. SETHIGH
3. SETLOW
4. GND (TWO PLACES) (CONNECTED TO SUBSTRATE)
5. VPTAT
6. UNDER
7. OVER
8. V+

For additional DICE ordering information, refer to databook.

ABSOLUTE MAXIMUM RATINGS

Maximum Supply Voltage . . . . –0.3 V to +15 V
Maximum Input Voltage
(SETHIGH, SETLOW) . . . .–0.3 V to [(V+) +0.3 V]
Maximum Output Current (VREF, VPTAT) . . . . 2 mA
Maximum Output Current (Open Collector Outputs) . . 50 mA
Maximum Output Voltage (Open Collector Outputs) . . . . 15 V
Operating Temperature Range . . . .–55°C to +150°C
Dice Junction Temperature . . . . +150°C
Storage Temperature Range . . . . – 65°C to +150°C
Lead Temperature (Soldering, 60 sec) . . . . +300°C

Package Type	θ_{JA}	θ_{JC}	Units
8-Pin Plastic DIP (P)	103[1]	43	°C/W
8-Lead SOIC (S)	158[2]	43	°C/W
8-Lead TO-99 Can (J)	150[1]	18	°C/W

NOTES
[1]θ_{JA} is specified for device in socket (worst case conditions).
[2]θ_{JA} is specified for device mounted on PCB.

CAUTION

1. Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation at or above this specification is not implied. Exposure to the above maximum rating conditions for extended periods may affect device reliability.
2. Digital inputs and outputs are protected, however, permanent damage may occur on unprotected units from high energy electrostatic fields. Keep units in conductive foam or packaging at all times until ready to use. Use proper antistatic handling procedures.
3. Remove power before inserting or removing units from their sockets.

ORDERING GUIDE

Model/Grade	Temperature Range[1]	Package Description	Package Option
TMP01EP	XIND	Plastic DIP	N-8
TMP01FP	XIND	Plastic DIP	N-8
TMP01ES	XIND	SOIC	SO-8
TMP01FS	XIND	SOIC	SO-8
TMP01FJ[2]	XIND	TO-99 Can	H-08A
TMP01GBC	+25°C	Die	

NOTES
[1]XIND = –40°C to +85°C.
[2]Consult factory for availability of MIL/883 version in TO-99 can.

GENERAL DESCRIPTION

The TMP01 is a very linear voltage-output temperature sensor, with a window comparator that can be programmed by the user to activate one of two open-collector outputs when a predetermined temperature setpoint voltage has been exceeded. A low drift voltage reference is available for setpoint programming.

The temperature sensor is basically a very accurately temperature compensated, bandgap-type voltage reference with a buffered output voltage proportional to absolute temperature (VPTAT), accurately trimmed to a scale factor of 5 mV/K. See the Applications Information following.

The low drift 2.5 V reference output VREF is easily divided externally with fixed resistors or potentiometers to accurately establish the programmed heat/cool setpoints, independent of temperature. Alternatively, the setpoint voltages can be supplied by other ground referenced voltage sources such as user-programmed DACs or controllers. The high and low setpoint voltages are compared to the temperature sensor voltage, thus creating a two-temperature thermostat function. In addition, the total output current of the reference (I_{VREF}) determines the magnitude of the temperature hysteresis band. The open collector outputs of the comparators can be used to control a wide variety of devices.

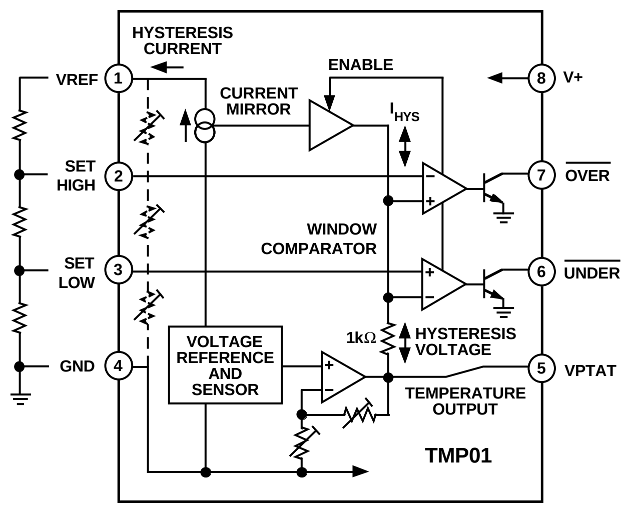


Figure 1. Detailed Block Diagram

Temperature Hysteresis

The temperature hysteresis is the number of degrees beyond the original setpoint temperature that must be sensed by the TMP01 before the setpoint comparator will be reset and the output disabled. Figure 2 shows the hysteresis profile. The hysteresis is programmed by the user by setting a specific load on the reference voltage output VREF. This output current I_{VREF} is also called the hysteresis current, which is mirrored internally and fed to a buffer with an analog switch.

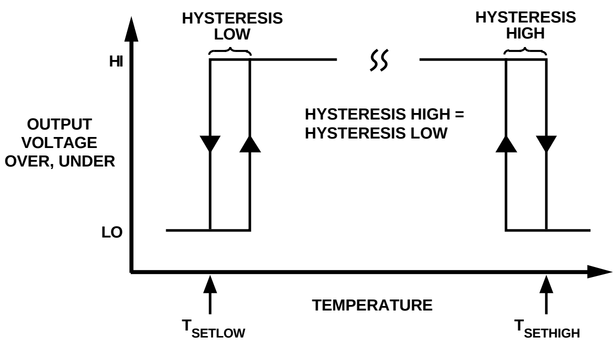


Figure 2. TMP01 Hysteresis Profile

After a temperature setpoint has been exceeded and a comparator tripped, the buffer output is enabled. The output is a current of the appropriate polarity which generates a hysteresis offset voltage across an internal 1000 Ω resistor at the comparator input. The comparator output remains "on" until the voltage at the comparator input, now equal to the temperature sensor voltage VPTAT summed with the hysteresis offset, has returned to the programmed setpoint voltage. The comparator then returns LOW, deactivating the open-collector output and disabling the hysteresis current buffer output. The scale factor for the programmed hysteresis current is:

$$I_{HYS} = I_{VREF} = 5\ \mu A/°C + 7\ \mu A$$

Thus since VREF = 2.5 V, with a reference load resistance of 357 kΩ or greater (output current 7 µA or less), the temperature setpoint hysteresis will be zero degrees. See the temperature programming discussion below. Larger values of load resistance will only decrease the output current below 7 µA and will have no effect on the operation of the device. The amount of hysteresis is determined by selecting a value of load resistance for VREF, as shown below.

Programming the TMP01

In the basic fixed-setpoint application utilizing a simple resistor ladder voltage divider, the desired temperature setpoints are programmed in the following sequence:

1. Select the desired hysteresis temperature.
2. Calculate the hysteresis current I_{VREF}.
3. Select the desired setpoint temperatures.
4. Calculate the individual resistor divider ladder values needed to develop the desired comparator setpoint voltages at SETHIGH and SETLOW.

The hysteresis current is readily calculated, as shown. For example, for 2 degrees of hysteresis, I_{VREF} = 17 µA. Next, the setpoint voltages $V_{SETHIGH}$ and V_{SETLOW} are determined using the VPTAT scale factor of 5 mV/K = 5 mV/(°C + 273.15), which is 1.49 V for +25°C. We then calculate the divider resistors, based on those setpoints. The equations used to calculate the resistors are:

$$V_{SETHIGH} = (T_{SETHIGH} + 273.15)(5\ mV/°C)$$

$$V_{SETLOW} = (T_{SETLOW} + 273.15)\ (5\ mV/°C)$$

$$R1\ (k\Omega) = (V_{VREF} - V_{SETHIGH})/I_{VREF} = (2.5\ V - V_{SETHIGH})/I_{VREF}$$

$$R2\ (k\Omega) = (V_{SETHIGH} - V_{SETLOW})/I_{VREF}$$

$$R3\ (k\Omega) = V_{SETLOW}/I_{VREF}$$

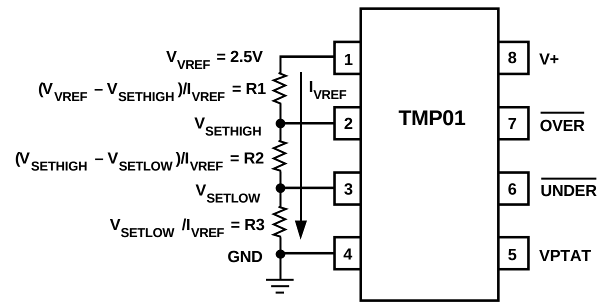


Figure 3. TMP01 Setpoint Programming

The total R1 + R2 + R3 is equal to the load resistance needed to draw the desired hysteresis current from the reference, or I_{VREF}.

The formulas shown above are also helpful in understanding the calculation of temperature setpoint voltages in circuits other than the standard two-temperature thermostat. If a setpoint function is not needed, the appropriate comparator should be disabled. SETHIGH can be disabled by tying it to V+, SETLOW by tying it to GND. Either output can be left unconnected.

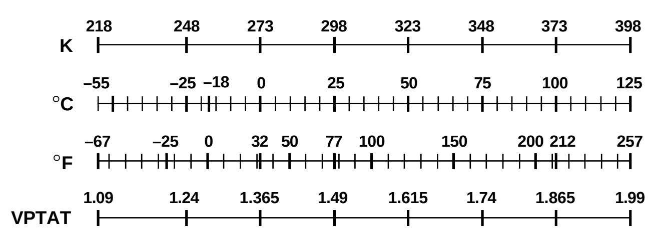


Figure 4. Temperature—VPTAT Scale

Understanding Error Sources

The accuracy of the VPTAT sensor output is well characterized and specified, however preserving this accuracy in a heating or cooling control system requires some attention to minimizing the various potential error sources. The internal sources of setpoint programming error include the initial tolerances and temperature drifts of the reference voltage VREF, the setpoint comparator input offset voltage and bias current, and the hysteresis current scale factor. When evaluating setpoint programming errors, remember that any VREF error contribution at the comparator inputs is reduced by the resistor divider ratios. The comparator input bias current (inputs SETHIGH, SETLOW) drops to less than 1 nA (typ) when the comparator is tripped. This can account for some setpoint voltage error, equal to the change in bias current times the effective setpoint divider ladder resistance to ground.

The thermal mass of the TMP01 package and the degree of thermal coupling to the surrounding circuitry are the largest factors in determining the rate of thermal settling, which ultimately determines the rate at which the desired temperature measurement accuracy may be reached. Thus, one must allow sufficient time for the device to reach the final temperature. The typical thermal time constant for the plastic package is approximately 140 seconds in still air! Therefore, to reach the final temperature accuracy within 1%, for a temperature change of 60 degrees, a settling time of 5 time constants, or 12 minutes, is necessary.

The setpoint comparator input offset voltage and zero hysteresis current affect setpoint error. While the 7 µA zero hysteresis current allows the user to program the TMP01 with moderate resistor divider values, it does vary somewhat from device to device, causing slight variations in the actual hysteresis obtained in practice. Comparator input offset directly impacts the programmed setpoint voltage and thus the resulting hysteresis band, and must be included in error calculations.

External error sources to consider are the accuracy of the programming resistors, grounding error voltages, and the overall problem of thermal gradients. The accuracy of the external programming resistors directly impacts the resulting setpoint accuracy. Thus in fixed-temperature applications the user should select resistor tolerances appropriate to the desired programming accuracy. Resistor temperature drift must be taken into account also. This effect can be minimized by selecting good quality components, and by keeping all components in close thermal proximity. Applications requiring high measurement accuracy require great attention to detail regarding thermal gradients. Careful circuit board layout, component placement, and protection from stray air currents are necessary to minimize common thermal error sources.

Also, the user should take care to keep the bottom of the setpoint programming divider ladder as close to GND (Pin 4) as possible to minimize errors due to IR voltage drops and coupling of external noise sources. In any case, a 0.1 µF capacitor for power supply bypassing is always recommended at the chip.

Safety Considerations In Heating And Cooling System Design

Designers should anticipate potential system fault conditions which may result in significant safety hazards which are outside the control of and cannot be corrected by the TMP01-based circuit. Governmental and industrial regulations regarding safety requirements and standards for such designs should be observed where applicable.

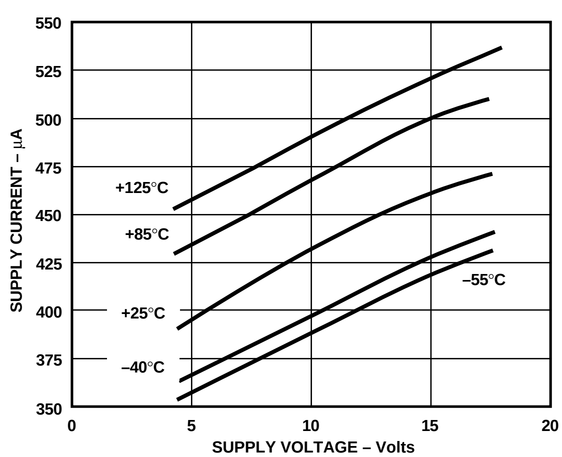


Figure 5. Supply Current vs. Supply Voltage

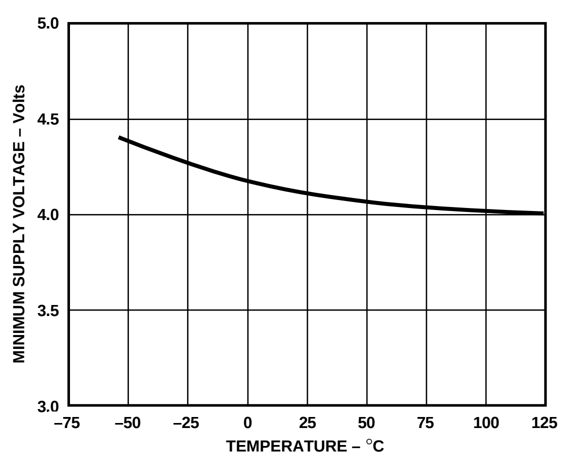


Figure 6. Minimum Supply Voltage vs. Temperature

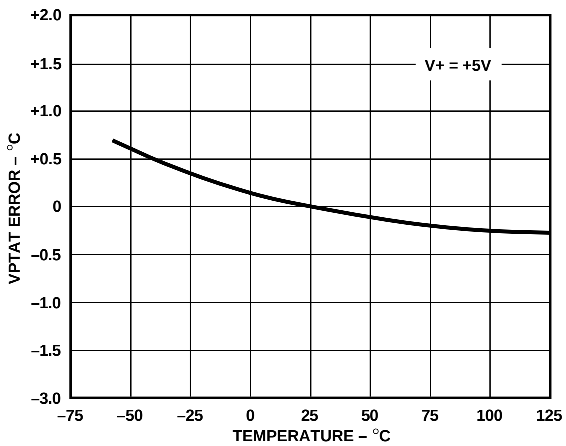


Figure 7. VPTAT Accuracy vs. Temperature

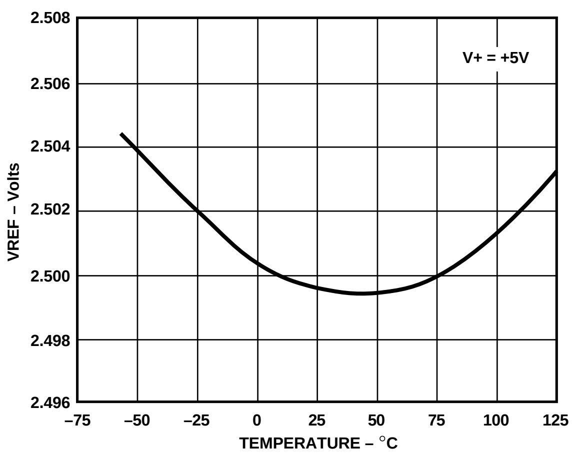


Figure 8. VREF Accuracy vs. Temperature

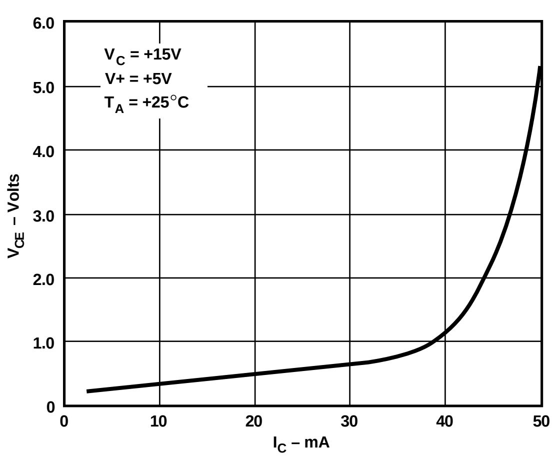


Figure 9. Open-Collector Output ($\overline{OVER}$, $\overline{UNDER}$) Saturation Voltage vs. Output Current

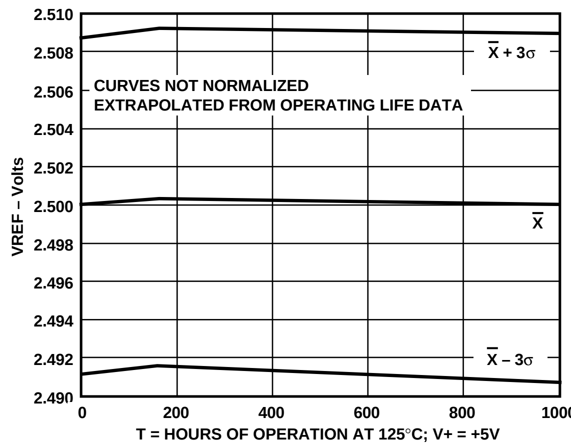


Figure 10. VREF Long Term Drift Accelerated by Burn-In

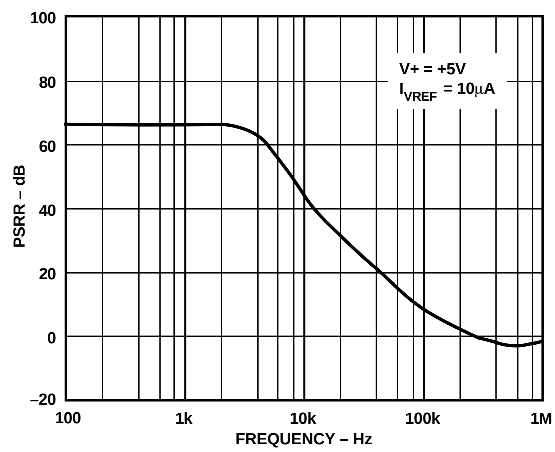


Figure 11. VREF Power Supply Rejection vs. Frequency

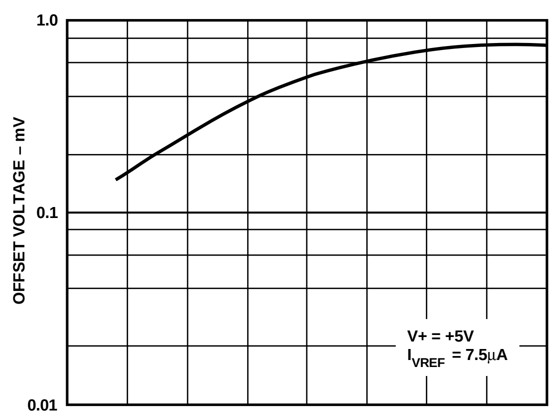


Figure 12. Set High, Set Low Input Offset Voltage vs. Temperature

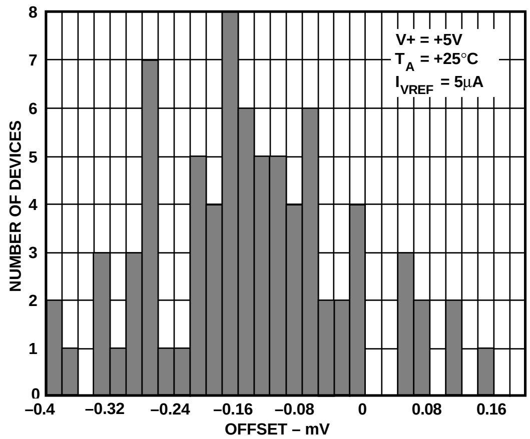


Figure 13. Comparator Input Offset Distribution

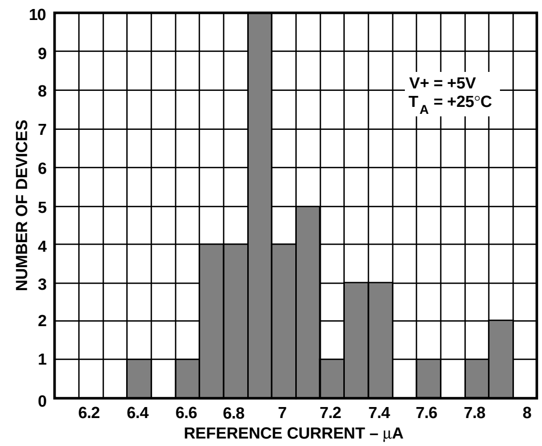


Figure 14. Zero Hysteresis Current Distribution

APPLICATIONS INFORMATION

Self-Heating Effects

In some applications the user should consider the effects of self-heating due to the power dissipated by the open-collector outputs, which are capable of sinking 20 mA continuously. Under full load, the TMP01 open-collector output device is dissipating

$$P_{DISS} = 0.6\ V \times .020A = 12\ mW$$

which in a surface-mount SO package accounts for a temperature increase due to self-heating of

$$\Delta T = P_{DISS} \times \theta_{JA} = .012\ W \times 158°C/W = 1.9°C.$$

This will of course directly affect the accuracy of the TMP01 and will for example cause the device to switch the heating output "OFF" 2 degrees early. Alternatively, bonding the same package to a moderate heatsink limits the self-heating effect to approximately

$$\Delta T = P_{DISS} \times \theta_{JC} = .012\ W \times 43°C/W = 0.52°C.$$

which is a much more tolerable error in most systems. The VREF and VPTAT outputs are also capable of delivering sufficient current to contribute heating effects and should not be ignored.

Buffering the Voltage Reference

As mentioned before, the reference output VREF is used to generate the temperature setpoint programming voltages for the TMP01 and also is used to determine the hysteresis temperature band by the reference load current I_{VREF}. The on-board output buffer amplifier is typically capable of 500 µA output drive into as much as 50 pF load (max). Exceeding this load will affect the accuracy of the reference voltage, could cause thermal sensing errors due to dissipation, and may induce oscillations. Selection of a low drift buffer functioning as a voltage follower with high input impedance will ensure optimal reference accuracy, and will not affect the programmed hysteresis current. Amplifiers which offer the low drift, low power consumption, and low cost appropriate to this application include the OP295, and members of the OP90, OP97, OP177 families, and others as shown in the following applications circuits.

With excellent drift and noise characteristics, VREF offers a good voltage reference for data acquisition and transducer excitation applications as well. Output drift is typically better than –10 ppm/°C, with 315 nV/$\sqrt{Hz}$ (typ) noise spectral density at 1 kHz.

Preserving Accuracy Over Wide Temperature Range Operation

The TMP01 is unique in offering both a wide-range temperature sensor and the associated detection circuitry needed to implement a complete thermostatic control function in one monolithic device. While the voltage reference, setpoint comparators, and output buffer amplifiers have been carefully compensated to maintain accuracy over the specified temperature range, the user has an additional task in maintaining the accuracy over wide operating temperature ranges in this application. Since the TMP01 is both sensor and control circuit, in many applications it is possible that the external components used to program and interface the device may be subjected to the same temperature extremes. Thus it may be necessary to locate components in close thermal proximity to minimize large temperature differentials, and to account for thermal drift errors where appropriate, such as resistor matching tempcos, amplifier error drift, and the like. Circuit design with the TMP01 requires a slightly different perspective regarding the thermal behavior of electronic components.

Thermal Response Time

The time required for a temperature sensor to settle to a specified accuracy is a function of the thermal mass of the sensor, and the thermal conductivity between the sensor and the object being sensed. Thermal mass is often considered equivalent to capacitance. Thermal conductivity is commonly specified using the symbol Q, and can be thought of as the reciprocal of thermal resistance. It is commonly specified in units of degrees per watt of power transferred across the thermal joint. Thus, the time required for the TMP01 to settle to the desired accuracy is dependent on the package selected, the thermal contact established in that particular application, and the equivalent power of the heat source. In most applications, the settling time is probably best determined empirically.

Switching Loads With The Open-Collector Outputs

In many temperature sensing and control applications some type of switching is required. Whether it be to turn on a heater when the temperature goes below a minimum value or to turn off a motor that is overheating, the open-collector outputs Over and Under can be used. For the majority of applications, the switches used need to handle large currents on the order of 1 amp and above. Because the TMP01 is accurately measuring temperature, the open-collector outputs should handle less than 20 mA of current to minimize self-heating. Clearly, the Over-temp and Under-temp outputs should not drive the equipment directly. Instead, an external switching device is required to handle the large currents. Some examples of these are relays, power MOSFETs, thyristors, IGBTs, and Darlingtons.

Figure 15 shows a variety of circuits where the TMP01 controls a switch. The main consideration in these circuits, such as the relay in Figure 15a, is the current required to activate the switch.

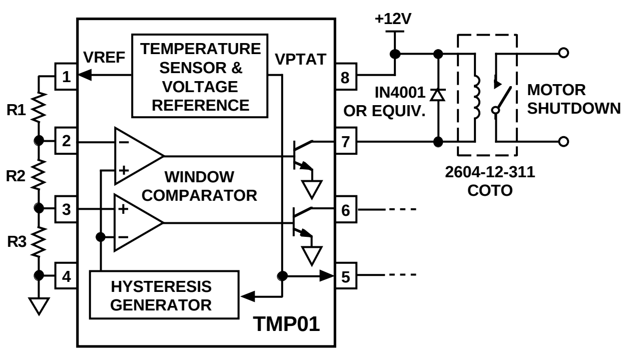


Figure 15a. Reed Relay Drive

It is important to check the particular relay you choose to ensure that the current needed to activate the coil does not exceed the TMP01's recommended output current of 20 mA. This is easily determined by dividing the relay coil voltage by the specified coil resistance. Keep in mind that the inductance of the relay will create large voltage spikes that can damage the TMP01 output unless protected by a commutation diode across the coil, as shown. The relay shown has a contact rating of 10 watts maximum. If a relay capable of handling more power is desired, the larger contacts will probably require a commensurately larger coil, with lower coil resistance and thus higher trigger current. As the contact power handling capability increases, so does the current needed for the coil. In some cases an external driving transistor should be used to remove the current load on the TMP01 as explained in the next section.

Power FETs are popular for handling a variety of high current DC loads. Figure 15b shows the TMP01 driving a p-channel MOSFET transistor for a simple heater circuit. When the output transistor turns on, the gate of the MOSFET is pulled down to approximately 0.6 V, turning it on. For most MOSFETs a gate-to-source voltage or Vgs on the order of –2 V to –5 V is sufficient to turn the device on. Figure 15c shows a similar circuit for turning on an n-channel MOSFET, except that now the gate to source voltage is positive. Because of this reason an external transistor must be used as an inverter so that the MOSFET will turn on when the "Under Temp" output pulls down.

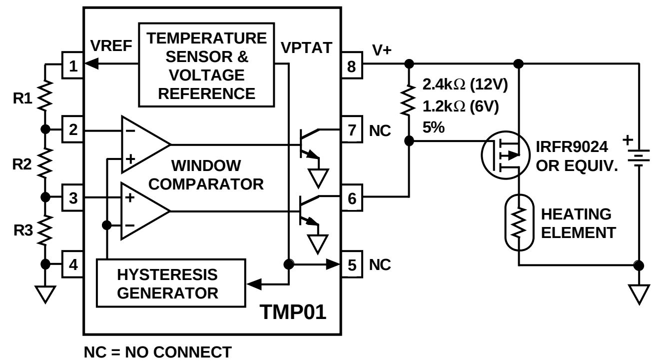


Figure 15b. Driving a P-Channel MOSFET

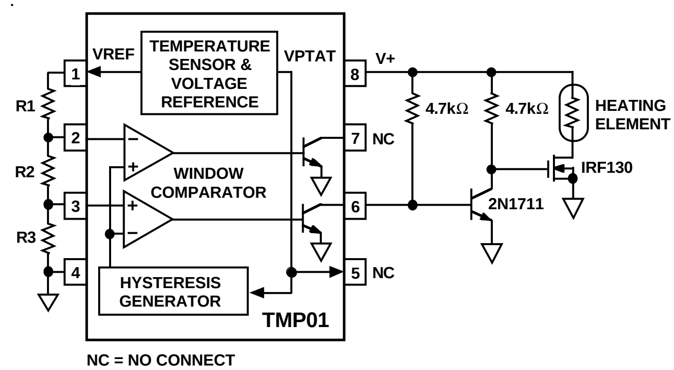


Figure 15c. Driving a N-Channel MOSFET

Isolated Gate Bipolar Transistors (IGBT) combine many of the benefits of power MOSFETs with bipolar transistors, and are used for a variety of high power applications. Because IGBTs have a gate similar to MOSFETs, turning on and off the devices is relatively simple as shown in Figure 15d. The turn on voltage for the IGBT shown (IRGBC40S) is between 3.0 and 5.5 volts. This part has a continuous collector current rating of 50 A and a maximum collector to emitter voltage of 600 V, enabling it to work in very demanding applications.

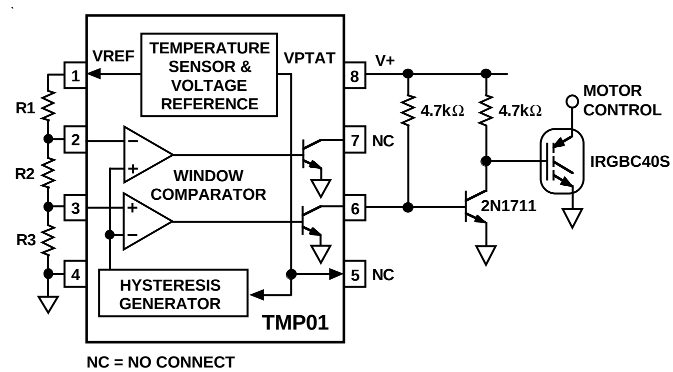


Figure 15d. Driving an IGBT

The last class of high power devices discussed here are Thyristors, which includes SCRs and Triacs. Triacs are a useful alternative to relays for switching ac line voltages. The 2N6073A shown in Figure 15e is rated to handle 4A (rms). The optoisolated MOC3011. Triac shown features excellent electrical isolation from the noisy ac line and complete control over the high power Triac with only a few additional components.

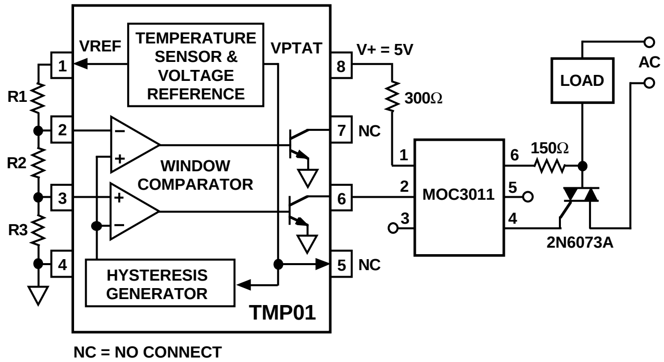


Figure 15e. Controlling the 2N6073A Triac

High Current Switching

As mentioned above, internal dissipation due to large loads on the TMP01 outputs will cause some temperature error due to self-heating. External transistors remove the load from the TMP01, so that virtually no power is dissipated in the internal transistors and no self-heating occurs. Figure 16 shows a few examples using external transistors. The simplest case, using a single transistor on the output to invert the output signal is shown in Figure 16a. When the open-collector of the TMP01 turns "ON" and pulls the output down, the external transistor Q1's base will be pulled low, turning off the transistor. Another transistor can be added to reinvert the signal as shown in Figure 16b. Now, when the output of the TMP01 is pulled down, the first transistor, Q1, turns off and its collector goes high, which turns Q2 on, pulling its collector low. Thus, the output taken from the collector of Q2 is identical to the output of the TMP01. By picking a transistor that can accommodate large amounts of current, many high power devices can be switched.

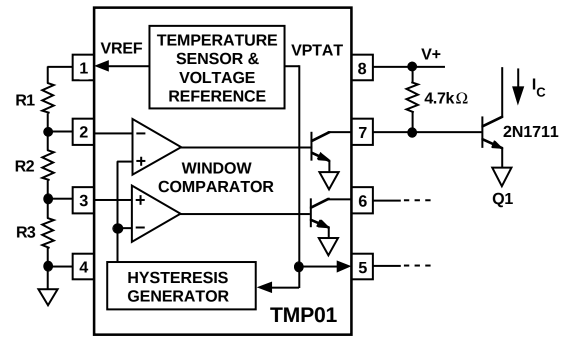


Figure 16a. An External Resistor Minimizes Self-Heating

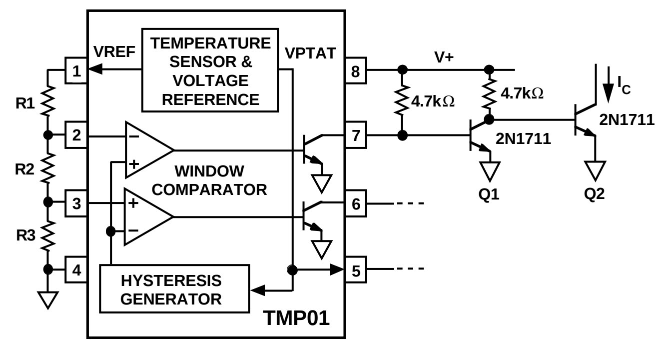


Figure 16b. Second Transistor Maintains Polarity of TMP01 Output

An example of a higher power transistor is a standard Darlington configuration as shown in Figure 16c. The part chosen, TIP-110, can handle 2A continuous which is more than enough to control many high power relays. In fact the Darlington itself can be used as the switch, similar to MOSFETs and IGBTs.

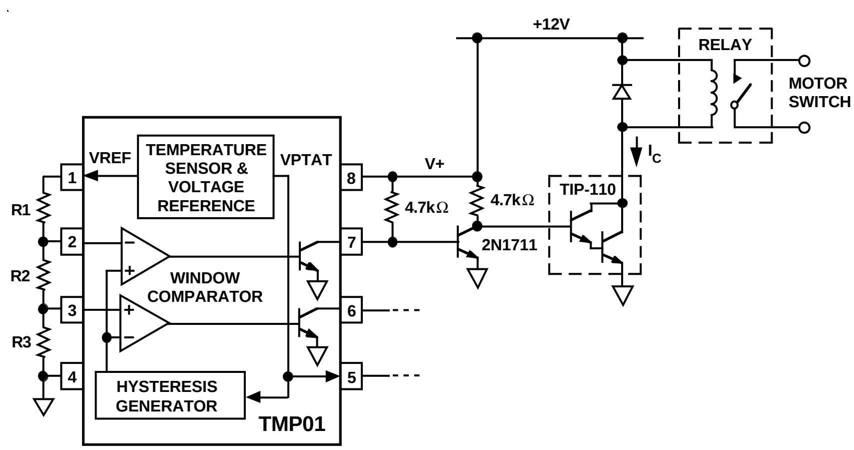


Figure 16c. Darlington Transistor Can Handle Large Currents

Buffering the Temperature Output Pin

The VPTAT sensor output is a low impedance dc output voltage with a 5 mV/K temperature coefficient, and is useful in a number of measurement and control applications. In many applications, this voltage needs to be transmitted to a central location for processing. The buffered VPTAT voltage output is capable of 500 μA drive into 50 pF (max). As mentioned in the discussion above regarding buffering circuits for the VREF output, it is useful to consider external amplifiers for interfacing VPTAT to external circuitry to ensure accuracy, and to minimize loading which could create dissipation-induced temperature sensing errors. An excellent general-purpose buffer circuit using the OP177 is shown in Figure 17 which is capable of driving over 10 mA, and will remain stable under capacitive loads of up to 0.1 μF. Other interfacing ideas are shown below.

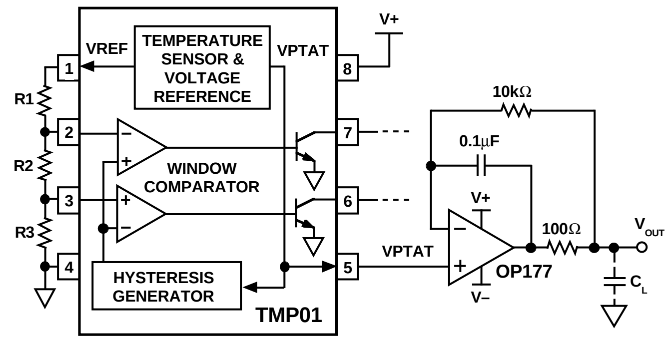


Figure 17. Buffer VPTAT to Handle Difficult Loads

Differential Transmitter

In noisy industrial environments, it is difficult to send an accurate analog signal over a significant distance. However, by sending the signal differentially on a wire pair, these errors can be significantly reduced. Since the noise will be picked up equally on both wires, a receiver with high common-mode input rejection can be used to cancel out the noise very effectively at the receiving end. Figure 18 shows two amplifiers being used to send the signal differentially, and an excellent differential receiver, the AMP03, which features a common-mode rejection ratio of 95 dB at dc and very low input and drift errors.

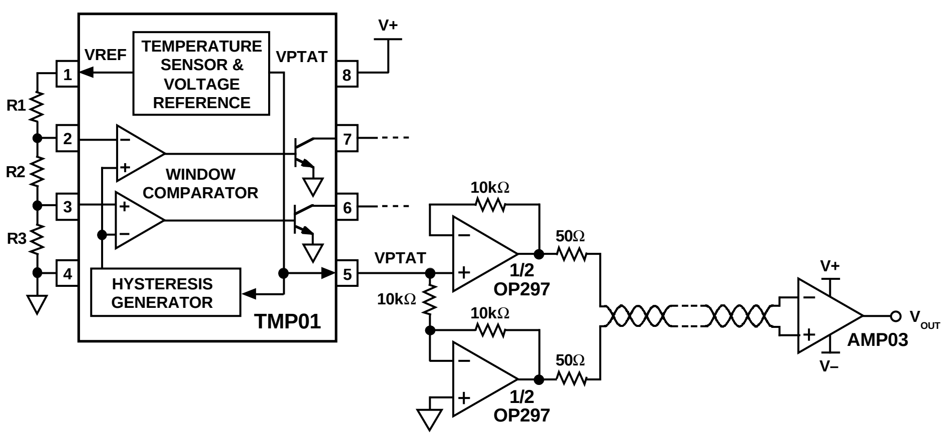


Figure 18. Send the Signal Differentially for Noise Immunity

4 mA-20 mA Current Loop

Another, very common method of transmitting a signal over long distances is to use a 4 mA-20 mA Loop, as shown in Figure 19. An advantage of using a 4 mA-20 mA loop is that the accuracy of a current loop is not compromised by voltage drops across the line. One requirement of 4 mA-20 mA circuits is that the remote end must receive all of its power from the loop, meaning that the circuit must consume less than 4 mA. Operating from +5 V, the quiescent current of the TMP01 is 500 µA max, and the OP90s is 20 µA max, totaling less than 4 mA. Although not shown, the open collector outputs and temperature setting pins can be connected to do any local control of switching.

The current is proportional to the voltage on the VPTAT output, and is calibrated to 4 mA at a temperature of –40°C, to 20 mA for +85°C. The main equation governing the operation of this circuit gives the current as a function of VPTAT:

$$I_{OUT} = \frac{1}{R6}\left(\frac{VPTAT \times R5}{R2} - \frac{VREF \times R3}{R3 + R1}\left(1 + \frac{R5}{R2}\right)\right)$$

The resulting temperature coefficient of the output current is 128 µA/°C.

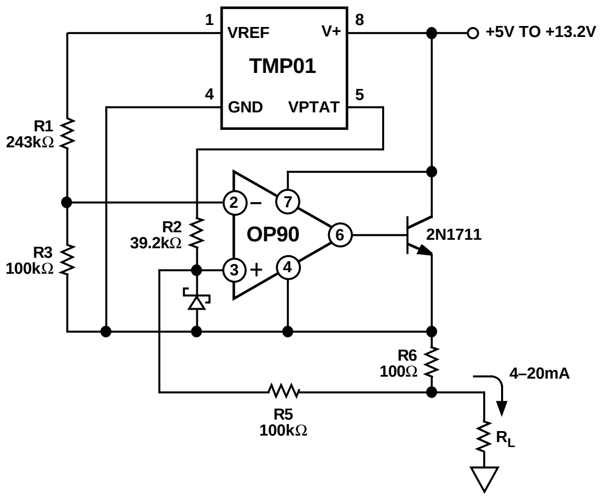


Figure 19. 4-20 mA Current Loop

To determine the resistor values in this circuit, first note that VREF remains constant over temperature. Thus the ratio of R5 over R2 must give a variation of I_{OUT} from 4 mA to 20 mA as VPTAT varies from 1.165 V at –40°C to 1.79 V at +85°C. The absolute value of the resistors is not important, only the ratio. For convenience, 100 kΩ is chosen for R5. Once R2 is calculated, the value of R3 and R1 is determined by substituting 4 mA for I_{OUT} and 1.165 V for VPTAT and solving. The final values are shown in the circuit. The OP90 is chosen for this circuit because of its ability to operate on a single supply and its high accuracy. For initial accuracy, a 10 kΩ trim potentiometer can be included in series with R3, and the value of R3 lowered to 95 kΩ. The potentiometer should be adjusted to produce an output current of 12.3 mA at 25°C.

Temperature-to-Frequency Converter

Another common method of transmitting analog information is to convert a voltage to the frequency domain. This is easily done with any of the low cost monolithic Voltage-to-Frequency Converters (VFCs) available, which feature a robust, open-collector digital output. A digital signal is very immune to noise and voltage drops because the only important information is the frequency. As long as the conversions between temperature and frequency are done accurately, the temperature data can be successfully transmitted.

A simple circuit to do this combines the TMP01 with an AD654 VFC, as shown in Figure 20. The AD654 outputs a square wave that is proportional to the dc input voltage according to the following equation:

$$F_{OUT} = \frac{V_{IN}}{10\,(R1 + R2)\,C_T}$$

By simply connecting the VPTAT output to the input of the AD654, the 5 mV/°C temperature coefficient gives a sensitivity of 25 Hz/°C, centered around 7.5 kHz at 25°C. The trimming resistor R2 is needed to calibrate the absolute accuracy of the AD654. For more information on that part, please consult the AD654 data sheet. Finally, the AD650 can be used to accurately convert the frequency back to a dc voltage on the receiving end.

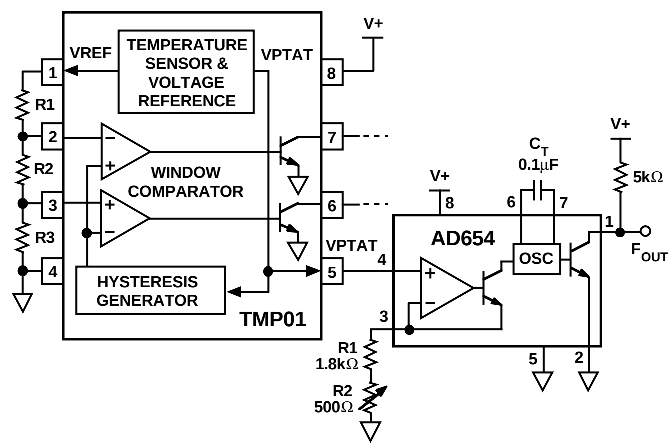


Figure 20. Temperature-to-Frequency Converter

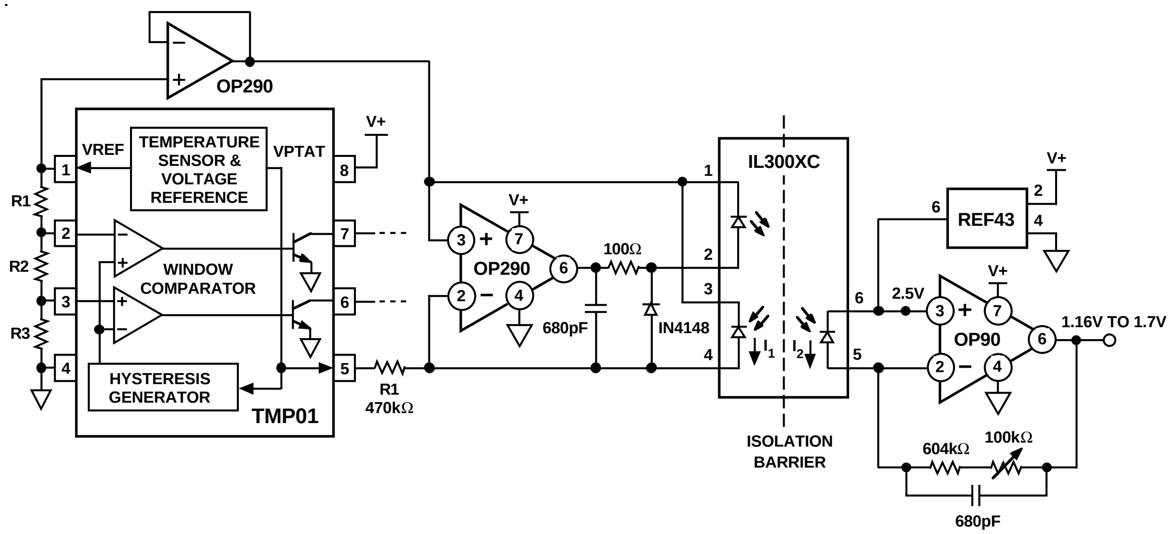


Figure 21. Isolation Amplifier

Isolation Amplifier

In many industrial applications the sensor is located in an environment that needs to be electrically isolated from the central processing area. Figure 21 shows a simple circuit that uses an 8-pin optoisolator (IL300XC) that can operate across a 5,000 V barrier. IC1 (an OP290 single-supply amplifier) is used to drive the LED connected between Pins 1 to 2. The feedback actually comes from the photodiode connected from Pins 3 to 4. The OP290 drives the LED such that there is enough current generated in the photodiode to exactly equal the current derived from the VPTAT voltage across the 470 kΩ resistor. On the receiving end, an OP90 converts the current from the second photodiode to a voltage through its feedback resistor R2. Note that the other amplifier in the dual OP290 is used to buffer the 2.5 V reference voltage of the TMP01 for an accurate, low drift LED bias level without affecting the programmed hysteresis current. A REF43 (a precision 2.5 V reference) provides an accurate bias level at the receiving end.

To understand this circuit, it helps to examine the overall equation for the output voltage. First, the current (I1) in the photodiode is set by:

$$I_1 = \frac{2.5\,V - VPTAT}{470\,k\Omega}$$

Note that the IL300XC has a gain of 0.73 (typical) with a min and max of 0.693 and 0.769 respectively. Since this is less than 1.0, R2 must be larger than R1 to achieve overall unity gain. To show this the full equation is:

$$V_{OUT} = 2.5\,V - I_2 R_2 = 2.5\,V - 0.7\left(\frac{2.5\,V - VPTAT}{470\,k\Omega}\right)644\,k\Omega = VPTAT$$

A trim is included for R2 to correct for the initial gain accuracy of the IL300XC. To perform this trim, simply adjust for an output voltage equal to VPTAT at any particular temperature. For example, at room temperature, VPTAT = 1.49 V, so adjust R2 until V_{OUT} = 1.49 V as well. Both the REF43 and the OP90 operate from a single supply, and contribute no significant error due to drift.

In order to avoid the accuracy trim, and to reduce board space, complete isolation amplifiers are available, such as the high accuracy AD202.

Out-of-Range Warning

By connecting the two open collector outputs of the TMP01 together into a "wired-OR" configuration, a temperature "out-of-range" warning signal is generated. This can be useful in sensitive equipment calibrated to work over a limited temperature range. R1, R2, and R3 in Figure 22 are chosen to give a temperature range of 10°C around room temperature (25°C). Thus, if the temperature in the equipment falls below +15°C or rises above +35°C, the Undertemp Output or Overtemp Output respectively will go low and turn the LED on. The LED may be replaced with a simple pull-up resistor to give a logic output for controlling the instrument, or any of the switching devices discussed above can be used.

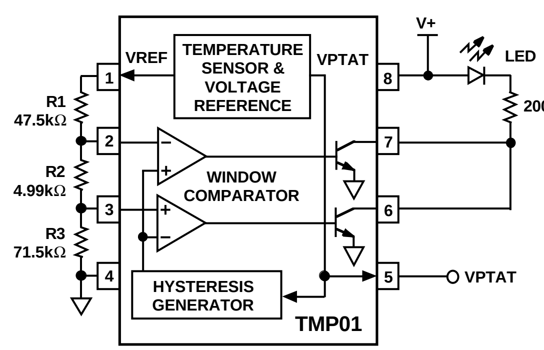


Figure 22. Out-of-Range Warning

Translating 5 mV/K to 10 mV/°C

A useful circuit is shown in Figure 23 that translates the VPTAT output voltage, which is calibrated in Kelvins, into an output that can be read directly in degrees Celsius on a voltmeter display. To accomplish this, an external amplifier is configured as a differential amplifier. The resistors are scaled so the VREF voltage will exactly cancel the VPTAT voltage at 0.0°C.

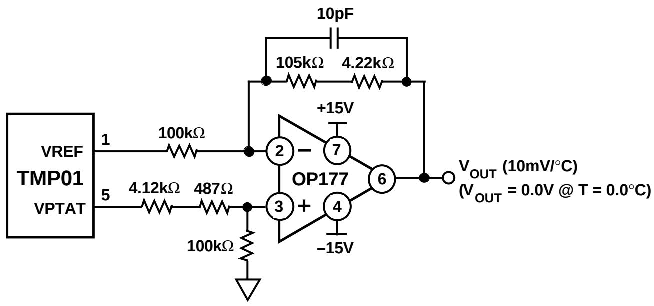


Figure 23. Translating 5 mV/K to 10 mV/°C

However, the gain from VPTAT to the output is two, so that 5 mV/K becomes 10 mV/°C. Thus, for a temperature of +80°C, the output voltage is 800 mV. Circuit errors will be due primarily to the inaccuracies of the resistor values. Using 1% resistors the observed error was less than 10 mV, or 1°C. The 10 pF feedback capacitor helps to ensure against oscillations. For better accuracy, a adjustment potentiometer can be added in series with either 100 kΩ resistor.

Translating VPTAT to the Fahrenheit Scale

A very similar circuit to the one shown in Figure 23 can be used to translate VPTAT into an output that can be read directly in degrees Fahrenheit, with a scaling of 10 mV/°F. Only unity gain or less is available from the first stage differentiating circuit, so the second amplifier provides a gain of two to complete the conversion to the Fahrenheit scale. Using the circuit in Figure 24, a temperature of 0.0°F gives an output of 0.00 V. At room temperature (70°F) the output voltage is 700 mV. A –40°C to +85°C operating range translates into –40°F to +185°F. The errors are essentially the same as for the circuit in Figure 23.

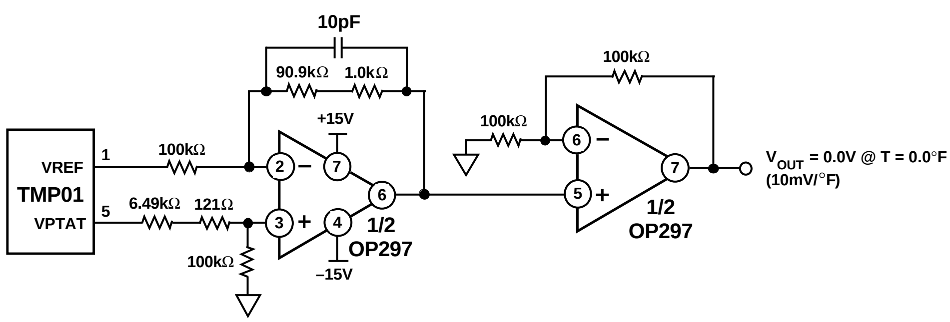
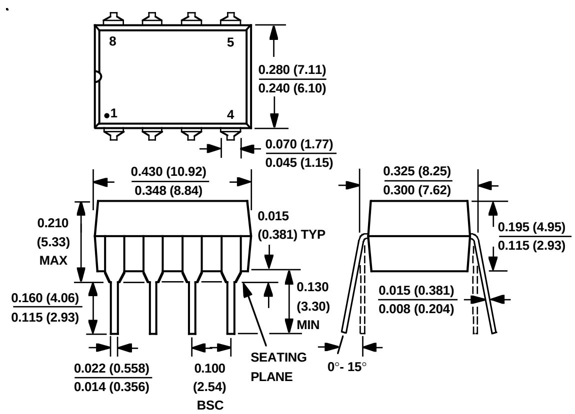


Figure 24. Translating 5 mV/K to 10 mV/°F

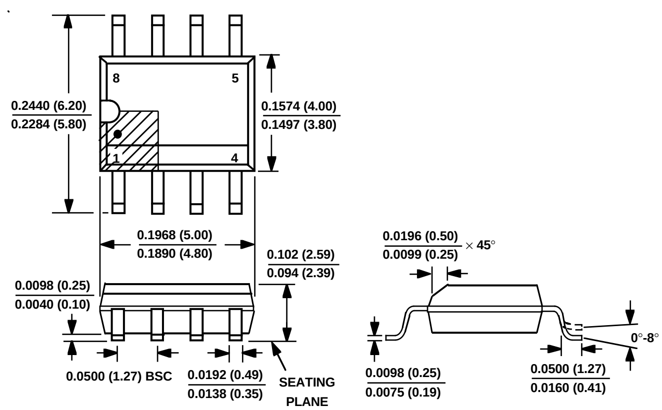
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

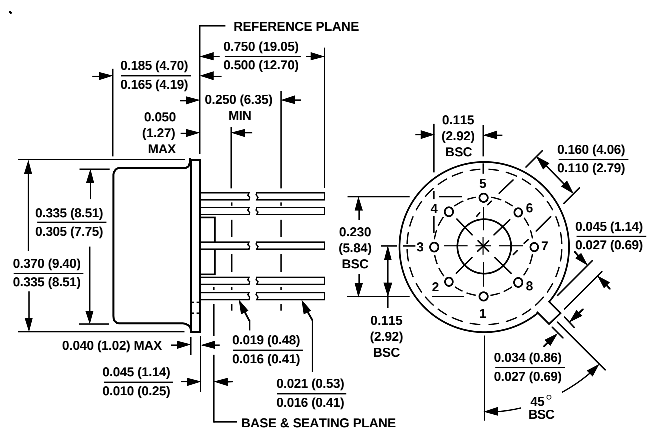
8-Pin Epoxy DIP



8-Pin SOIC



8-Pin TO-99



C1802b–5–7/95

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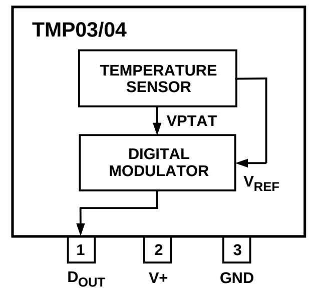
Serial Digital Output Thermometers

TMP03/TMP04*

FEATURES
- Low Cost 3-Pin Package
- Modulated Serial Digital Output Proportional to Temperature
- ±1.5°C Accuracy (typ) from –25°C to +100°C
- Specified –40°C to +100°C, Operation to 150°C
- Power Consumption 6.5 mW Max at 5 V
- Flexible Open-Collector Output on TMP03
- CMOS/TTL Compatible Output on TMP04
- Low Voltage Operation (4.5 V to 7 V)

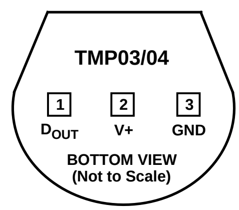
APPLICATIONS
- Isolated Sensors
- Environmental Control Systems
- Computer Thermal Monitoring
- Thermal Protection
- Industrial Process Control
- Power System Monitors

FUNCTIONAL BLOCK DIAGRAM

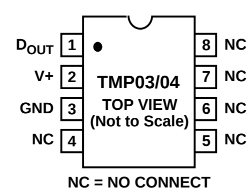


PACKAGE TYPES AVAILABLE

TO-92



SO-8 and RU-8 (TSSOP)



GENERAL DESCRIPTION

The TMP03/TMP04 is a monolithic temperature detector that generates a modulated serial digital output that varies in direct proportion to the temperature of the device. An onboard sensor generates a voltage precisely proportional to absolute temperature which is compared to an internal voltage reference and input to a precision digital modulator. The ratiometric encoding format of the serial digital output is independent of the clock drift errors common to most serial modulation techniques such as voltage-to-frequency converters. Overall accuracy is ±1.5°C (typical) from –25°C to +100°C, with excellent transducer linearity. The digital output of the TMP04 is CMOS/TTL compatible, and is easily interfaced to the serial inputs of most popular microprocessors. The open-collector output of the TMP03 is capable of sinking 5 mA. The TMP03 is best suited for systems requiring isolated circuits utilizing optocouplers or isolation transformers.

The TMP03 and TMP04 are specified for operation at supply voltages from 4.5 V to 7 V. Operating from +5 V, supply current (unloaded) is less than 1.3 mA.

The TMP03/TMP04 are rated for operation over the –40°C to +100°C temperature range in the low cost TO-92, SO-8, and TSSOP-8 surface mount packages. Operation extends to +150°C with reduced accuracy.

(continued on page 4)

***Patent pending.**

REV. 0

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 617/329-4700 **Fax: 617/326-8703**

TMP03/TMP04–SPECIFICATIONS

TMP03F (V+ = +5 V, –40°C ≤ T_A ≤ 100°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
ACCURACY						
Temperature Error		T_A = +25°C		1.0	3.0	°C
		–25°C < T_A < +100°C[1]		1.5	4.0	°C
		–40°C < T_A < –25°C[1]		2.0	5.0	°C
Temperature Linearity				0.5		°C
Long-Term Stability		1000 Hours at +125°C		0.5		°C
Nominal Mark-Space Ratio	T1/T2	T_A = 0°C		58.8		%
Nominal T1 Pulse Width	T1			10		ms
Power Supply Rejection Ratio	PSRR	Over Rated Supply T_A = +25°C		0.7	1.2	°C/V
OUTPUTS						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA			0.2	V
Output Low Voltage	V_{OL}	I_{SINK} = 5 mA 0°C < T_A < +100°C			2	V
Output Low Voltage	V_{OL}	I_{SINK} = 4 mA –40°C < T_A < 0°C			2	V
Digital Output Capacitance	C_{OUT}	(Note 2)		15		pF
Fall Time	t_{HL}	See Test Load		150		ns
Device Turn-On Time				20		ms
POWER SUPPLY						
Supply Range	V+		4.5		7	V
Supply Current	I_{SY}	Unloaded		0.9	1.3	mA

NOTES
[1]Maximum deviation from output transfer function over specified temperature range.
[2]Guaranteed but not tested.
Specifications subject to change without notice.

Test Load
10 kΩ to +5 V Supply, 100 pF to Ground

TMP04F (V+ = +5 V, –40°C ≤ T_A ≤ +100°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
ACCURACY						
Temperature Error		T_A = +25°C		1.0	3.0	°C
		–25°C < T_A < +100°C[1]		1.5	4.0	°C
		–40°C < T_A < –25°C[1]		2.0	5.0	°C
Temperature Linearity				0.5		°C
Long-Term Stability		1000 Hours at +125°C		0.5		°C
Nominal Mark-Space Ratio	T1/T2	T_A = 0°C		58.8		%
Nominal T1 Pulse Width	T1			10		ms
Power Supply Rejection Ratio	PSRR	Over Rated Supply T_A = +25°C		0.7	1.2	°C/V
OUTPUTS						
Output High Voltage	V_{OH}	I_{OH} = 800 μA	V+ –0.4			V
Output Low Voltage	V_{OL}	I_{OL} = 800 μA			0.4	V
Digital Output Capacitance	C_{OUT}	(Note 2)		15		pF
Fall Time	t_{HL}	See Test Load		200		ns
Rise Time	t_{LH}	See Test Load		160		ns
Device Turn-On Time				20		ms
POWER SUPPLY						
Supply Range	V+		4.5		7	V
Supply Current	I_{SY}	Unloaded		0.9	1.3	mA

NOTES
[1]Maximum deviation from output transfer function over specified temperature range.
[2]Guaranteed but not tested.
Specifications subject to change without notice.

Test Load
100 pF to Ground

WAFER TEST LIMITS (V+ = +5 V, GND = 0 V, T_A = +25°C, unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
ACCURACY						
Temperature Error		T_A = +25°C[1]			3.0	°C
Power Supply Rejection Ratio	PSRR	Over Rated Supply			1.2	°C/V
OUTPUTS						
Output High Voltage, TMP04	V_{OH}	I_{OH} = 800 μA	V+ – 0.4			V
Output Low Voltage, TMP04	V_{OL}	I_{OL} = 800 μA			0.4	V
Output Low Voltage, TMP03	V_{OL}	I_{SINK} = 1.6 mA			0.2	V
POWER SUPPLY						
Supply Range	V+		4.5		7	V
Supply Current	I_{SY}	Unloaded			1.3	mA

NOTES
Electrical tests are performed at wafer probe to the limits shown. Due to variations in assembly methods and normal yield loss, yield after packaging is not guaranteed for standard product dice. Consult factory to negotiate specifications based on dice lot qualification through sample lot assembly and testing.
[1]Maximum deviation from ratiometric output transfer function over specified temperature range.

ABSOLUTE MAXIMUM RATINGS*

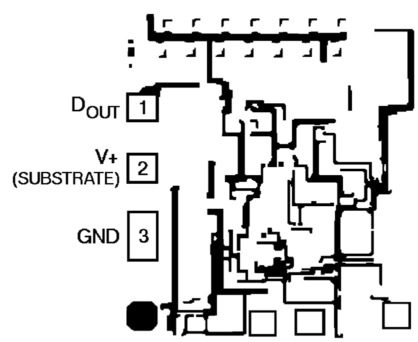
Maximum Supply Voltage . . . . +9 V
Maximum Output Current (TMP03 D_{OUT}) . . . . 50 mA
Maximum Output Current (TMP04 D_{OUT}) . . . . 10 mA
Maximum Open-Collector Output Voltage (TMP03) . . +18 V
Operating Temperature Range . . . . –55°C to +150°C
Dice Junction Temperature . . . . +175°C
Storage Temperature Range . . . . –65°C to +160°C
Lead Temperature (Soldering, 60 sec) . . . . +300°C

***CAUTION**
[1]Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation at or above this specification is not implied. Exposure to the above maximum rating conditions for extended periods may affect device reliability.
[2]Digital inputs and outputs are protected, however, permanent damage may occur on unprotected units from high-energy electrostatic fields. Keep units in conductive foam or packaging at all times until ready to use. Use proper antistatic handling procedures.
[3]Remove power before inserting or removing units from their sockets.

Package Type	Θ_{JA}	Θ_{JC}	Units
TO-92 (T9)	162[1]	120	°C/W
SO-8 (S)	158[1]	43	°C/W
TSSOP (RU)	240[1]	43	°C/W

NOTE
[1]Θ_{JA} is specified for device in socket (worst case conditions).

DICE CHARACTERISTICS



Die Size 0.050 × 0.060 inch, 3,000 sq. mils
(1.27 × 1.52 mm, 1.93 sq. mm)

For additional DICE ordering information, refer to databook.

ORDERING GUIDE

Model	Accuracy at +25°C	Temperature Range	Package
TMP03FT9	±3.0	XIND	TO-92
TMP03FS	±3.0	XIND	SO-8
TMP03FRU	±3.0	XIND	TSSOP-8
TMP03GBC	±3.0	+25°C	Die
TMP04FT9	±3.0	XIND	TO-92
TMP04FS	±3.0	XIND	SO-8
TMP04FRU	±3.0	XIND	TSSOP-8
TMP04GBC	±3.0	+25°C	Die

CAUTION
ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the TMP03/TMP04 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

(continued from page 1)

The TMP03/TMP04 is a powerful, complete temperature measurement system with digital output, on a single chip. The onboard temperature sensor follows in the footsteps of the TMP01 low power programmable temperature controller, offering excellent accuracy and linearity over the entire rated temperature range without correction or calibration by the user.

The sensor output is digitized by a first-order sigma-delta modulator, also known as the "charge balance" type analog-to-digital converter. (See Figure 1.) This type of converter utilizes time-domain oversampling and a high accuracy comparator to deliver 12 bits of effective accuracy in an extremely compact circuit.

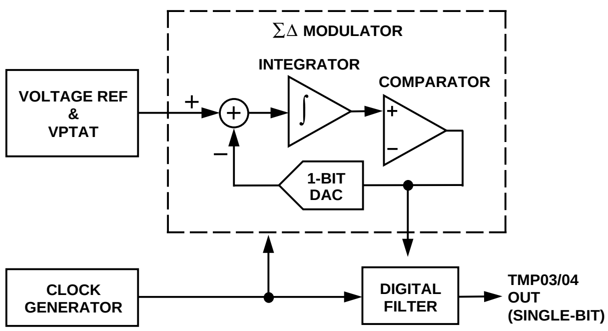


Figure 1. TMP03/TMP04 Block Diagram Showing First-Order Sigma-Delta Modulator

Basically, the sigma-delta modulator consists of an input sampler, a summing network, an integrator, a comparator, and a 1-bit DAC. Similar to the voltage-to-frequency converter, this architecture creates in effect a negative feedback loop whose intent is to minimize the integrator output by changing the duty cycle of the comparator output in response to input voltage changes. The comparator samples the output of the integrator at a much higher rate than the input sampling frequency, called oversampling. This spreads the quantization noise over a much wider band than that of the input signal, improving overall noise performance and increasing accuracy.

The modulated output of the comparator is encoded using a circuit technique (patent pending) which results in a serial digital signal with a mark-space ratio format that is easily decoded by any microprocessor into either degrees centigrade or degrees Fahrenheit values, and readily transmitted or modulated over a single wire. Most importantly, this encoding method neatly avoids major error sources common to other modulation techniques, as it is clock-independent.

Output Encoding

Accurate sampling of an analog signal requires precise spacing of the sampling interval in order to maintain an accurate representation of the signal in the time domain. This dictates a master clock between the digitizer and the signal processor. In the case of compact, cost-effective data acquisition systems, the addition of a buffered, high speed clock line can represent a significant burden on the overall system design. Alternatively, the addition of an onboard clock circuit with the appropriate accuracy and drift performance to an integrated circuit can add significant cost. The modulation and encoding techniques utilized in the TMP03/TMP04 avoid this problem and allow the overall circuit to fit into a compact, three-pin package. To achieve this, a simple, compact onboard clock and an oversampling digitizer that is insensitive to sampling rate variations are used. Most importantly, the digitized signal is encoded into a ratiometric format in which the exact frequency of the TMP03/TMP04's clock is irrelevant, and the effects of clock variations are effectively canceled upon decoding by the digital filter.

The output of the TMP03/TMP04 is a square wave with a nominal frequency of 35 Hz (±20%) at +25°C. The output format is readily decoded by the user as follows:

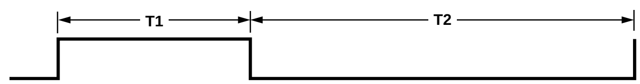


Figure 2. TMP03/TMP04 Output Format

$$\text{Temperature (°C)} = 235 - \left(\frac{400 \times T1}{T2}\right)$$

$$\text{Temperature (°F)} = 455 - \left(\frac{720 \times T1}{T2}\right)$$

The time periods T1 (high period) and T2 (low period) are values easily read by a microprocessor timer/counter port, with the above calculations performed in software. Since both periods are obtained consecutively, using the same clock, performing the division indicated in the above formulas results in a ratiometric value that is independent of the exact frequency of, or drift in, either the originating clock of the TMP03/TMP04 or the user's counting clock.

Table I. Counter Size and Clock Frequency Effects on Quantization Error

Maximum Count Available	Maximum Temp Required	Maximum Frequency	Quantization Error (+25°C)	Quantization Error (+77°F)
4096	+125°C	94 kHz	0.284°C	0.512°F
8192	+125°C	188 kHz	0.142°C	0.256°F
16384	+125°C	376 kHz	0.071°C	0.128°F

Optimizing Counter Characteristics

Counter resolution, clock rate, and the resultant temperature decode error that occurs using a counter scheme may be determined from the following calculations:

1. T1 is nominally 10 ms, and compared to T2 is relatively insensitive to temperature changes. A useful worst-case assumption is that T1 will never exceed 12 ms over the specified temperature range.

   T1 max = 12 ms

   Substituting this value for T1 in the formula, temperature (°C) = 235 – ([T1/T2] × 400), yields a maximum value of T2 of 44 ms at 125°C. Rearranging the formula allows the maximum value of T2 to be calculated at any maximum operating temperature:

   T2 (Temp) = (T1max × 400)/(235 – Temp) in seconds

2. We now need to calculate the maximum clock frequency we can apply to the gated counter so it will not overflow during T2 time measurement. The maximum frequency is calculated using:

   Frequency (max) = Counter Size/ (T2 at maximum temperature)

   Substituting in the equation using a 12-bit counter gives, Fmax = 4096/44 ms ≃ 94 kHz.

3. Now we can calculate the temperature resolution, or quantization error, provided by the counter at the chosen clock frequency and temperature of interest. Again, using a 12-bit counter being clocked at 90 kHz (to allow for ~5% temperature over-range), the temperature resolution at +25°C is calculated from:

   Quantization Error (°C) = 400 × ([Count1/Count2] – [Count1 – 1]/[Count2 + 1])

   Quantization Error (°F) = 720 × ([Count1/Count2] – [Count1 – 1]/[Count2 + 1])

   where, *Count1* = T1max × Frequency, and *Count2* = T2 (Temp) × Frequency. At +25°C this gives a resolution of better than 0.3°C. Note that the temperature resolution calculated from these equations improves as temperature increases. Higher temperature resolution will be obtained by employing larger counters as shown in Table I. The internal quantization error of the TMP03/TMP04 sets a theoretical minimum resolution of approximately 0.1°C at +25°C.

Self-Heating Effects

The temperature measurement accuracy of the TMP03/TMP04 may be degraded in some applications due to self-heating. Errors introduced are from the quiescent dissipation, and power dissipated by the digital output. The magnitude of these temperature errors is dependent on the thermal conductivity of the TMP03/TMP04 package, the mounting technique, and effects of airflow. Static dissipation in the TMP03/TMP04 is typically 4.5 mW operating at 5 V with no load. In the TO-92 package mounted in free air, this accounts for a temperature increase due to self-heating of

$$\Delta T = P_{DISS} \times \Theta_{JA} = 4.5\ mW \times 162°C/W = 0.73°C\ \ (1.3°F)$$

For a free-standing surface-mount TSSOP package, the temperature increase due to self-heating would be

$$\Delta T = P_{DISS} \times \Theta_{JA} = 4.5\ mW \times 240°C/W = 1.08°C\ \ (1.9°F)$$

In addition, power is dissipated by the digital output which is capable of sinking 800 µA continuous (TMP04). Under full load, the output may dissipate

$$P_{DISS} = (0.6\ V)(0.8\ mA)\left(\frac{T2}{T1+T2}\right)$$

For example with T2 = 20 ms and T1 = 10 ms, the power dissipation due to the digital output is approximately 0.32 mW with a 0.8 mA load. In a free-standing TSSOP package this accounts for a temperature increase due to output self-heating of

$$\Delta T = P_{DISS} \times \Theta_{JA} = 0.32\ mW \times 240°C/W = 0.08°C\ \ (0.14°F)$$

This temperature increase adds directly to that from the quiescent dissipation and affects the accuracy of the TMP03/TMP04 relative to the true ambient temperature. Alternatively, when the same package has been bonded to a large plate or other thermal mass (effectively a large heatsink) to measure its temperature, the total self-heating error would be reduced to approximately

$$\Delta T = P_{DISS} \times \Theta_{JC} = (4.5\ mW + 0.32\ mW) \times 43°C/W = 0.21°C\ (0.37°F)$$

Calibration

The TMP03 and TMP04 are laser-trimmed for accuracy and linearity during manufacture and, in most cases, no further adjustments are required. However, some improvement in performance can be gained by additional system calibration. To perform a single-point calibration at room temperature, measure the TMP03/TMP04 output, record the actual measurement temperature, and modify the offset constant (normally 235; see the Output Encoding section) as follows:

$$Offset\ Constant = 235 + (T_{OBSERVED} - T_{TMP03OUTPUT})$$

A more complicated two-point calibration is also possible. This involves measuring the TMP03/TMP04 output at two temperatures, Temp1 and Temp2, and modifying the slope constant (normally 400) as follows:

$$Slope\ Constant = \frac{Temp2 - Temp1}{\left(\frac{T1\ @\ Temp1}{T2\ @\ Temp1}\right) - \left(\frac{T1\ @\ Temp2}{T2\ @\ Temp2}\right)}$$

where $T1$ and $T2$ are the output high and output low times, respectively.

TMP03/TMP04–Typical Performance Characteristics

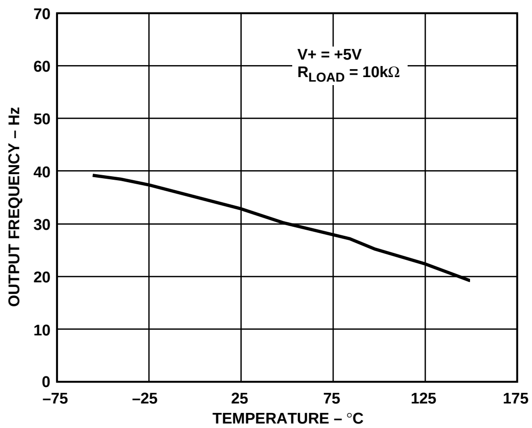


Figure 3. Output Frequency vs. Temperature

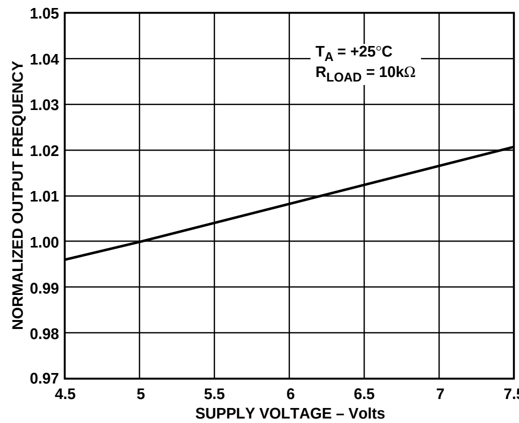


Figure 6. Normalized Output Frequency vs. Supply Voltage

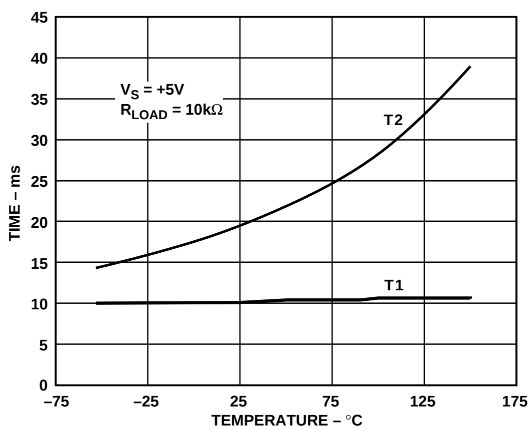


Figure 4. T1 and T2 Times vs. Temperature

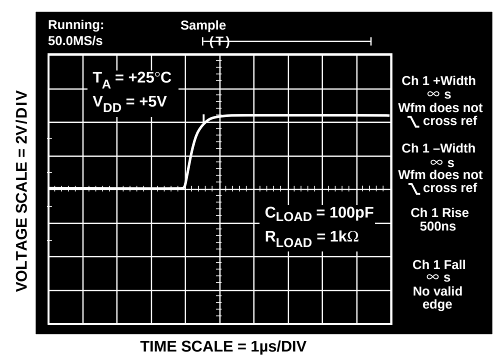


Figure 7. TMP03 Output Rise Time at +25°C

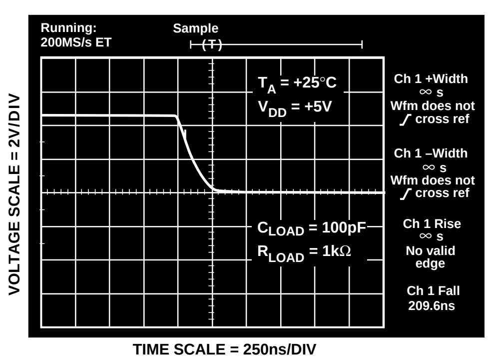


Figure 5. TMP03 Output Fall Time at +25°C

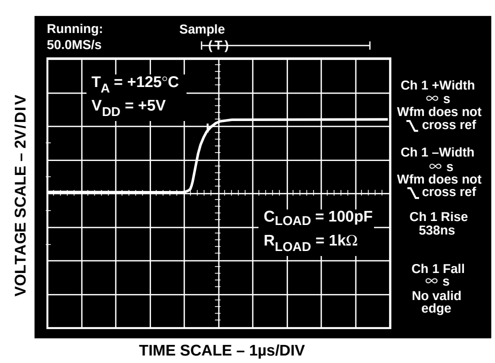


Figure 8. TMP03 Output Rise Time at +125°C

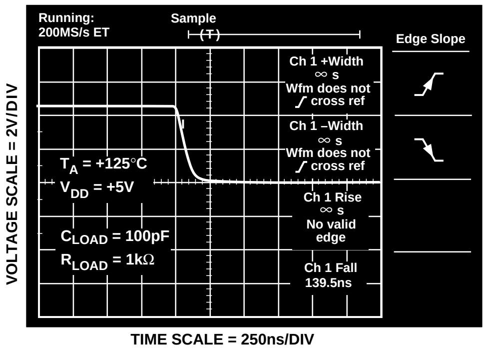


Figure 9. TMP03 Output Fall Time at +125°C

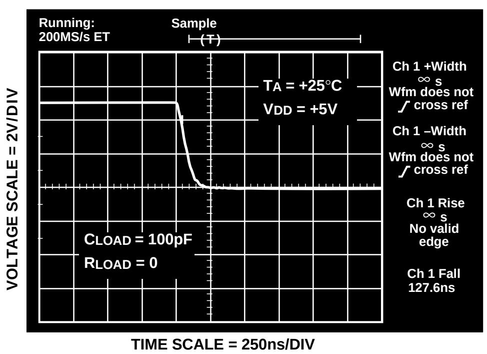


Figure 10. TMP04 Output Fall Time at +25°C

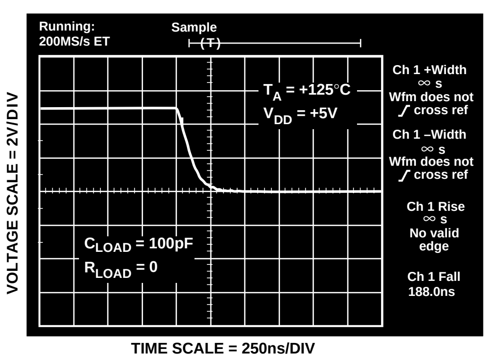


Figure 11. TMP04 Output Fall Time at +125°C

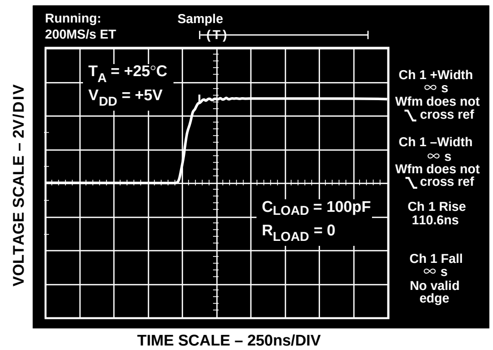


Figure 12. TMP04 Output Rise Time at +25°C

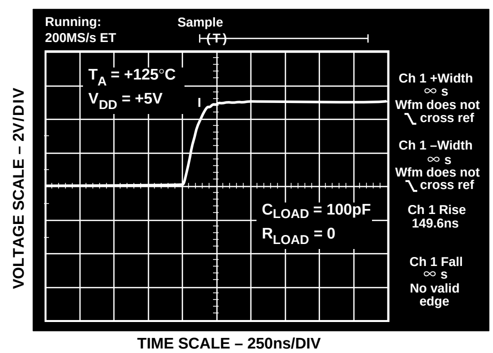


Figure 13. TMP04 Output Rise Time at +125°C

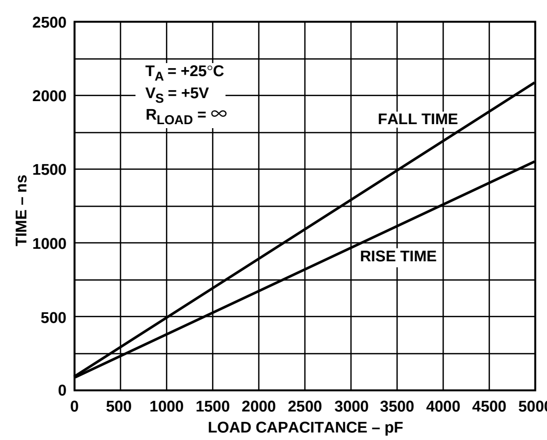


Figure 14. TMP04 Output Rise & Fall Times vs. Capacitive Load

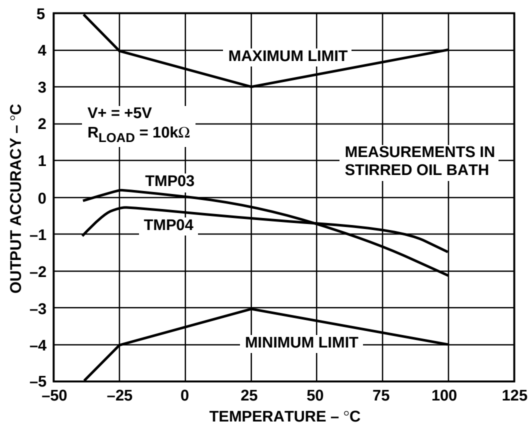


Figure 15. Output Accuracy vs. Temperature

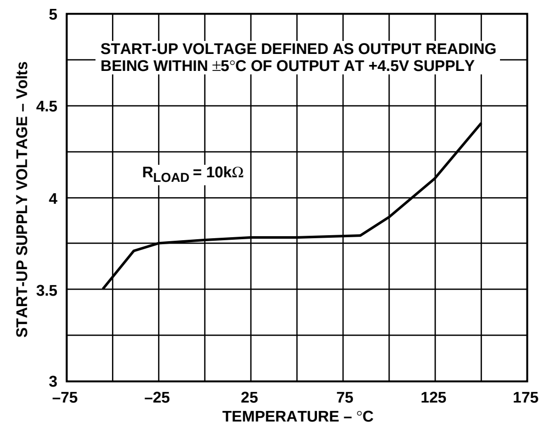


Figure 18. Start-Up Voltage vs. Temperature

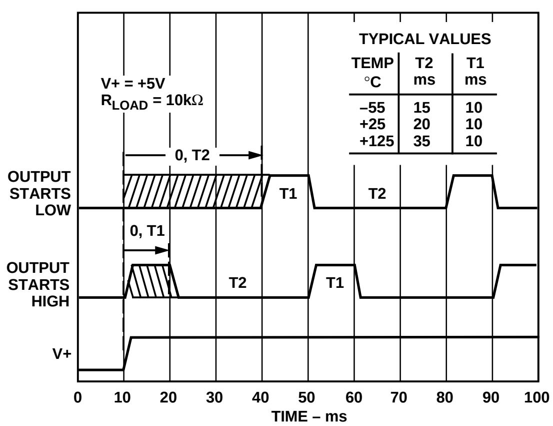


Figure 16. Start-Up Response

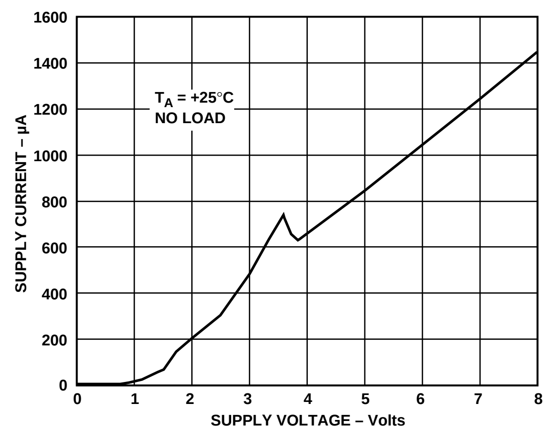


Figure 19. Supply Current vs. Supply Voltage

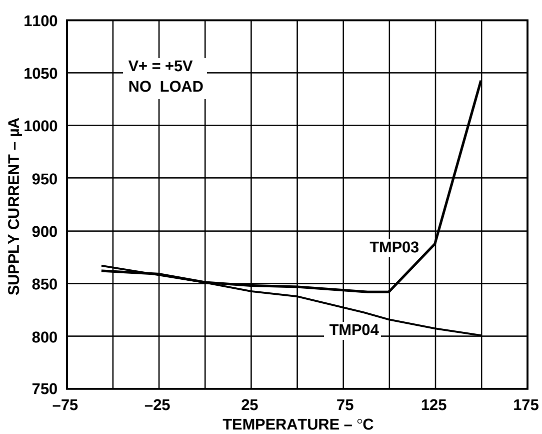


Figure 17. Supply Current vs. Temperature

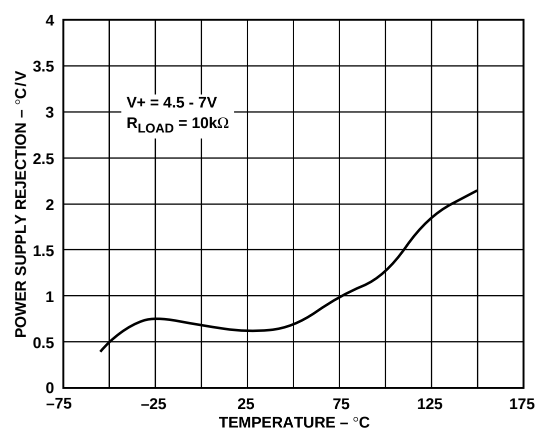


Figure 20. Power Supply Rejection vs. Temperature

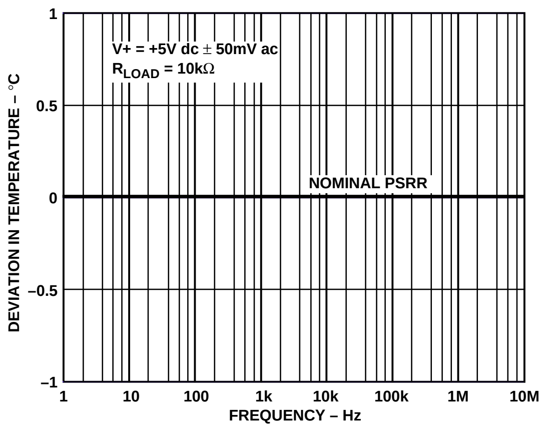


Figure 21. Power Supply Rejection vs. Frequency

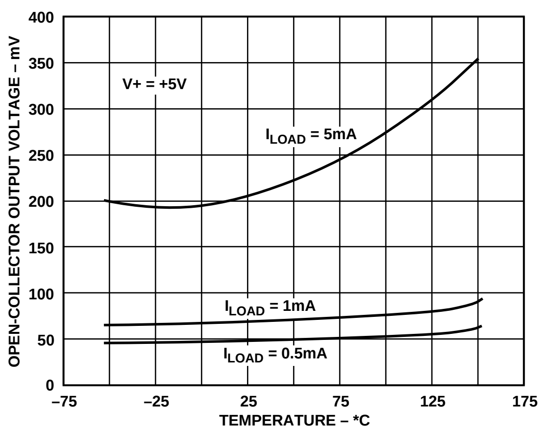


Figure 22. TMP03 Open-Collector Output Voltage vs. Temperature

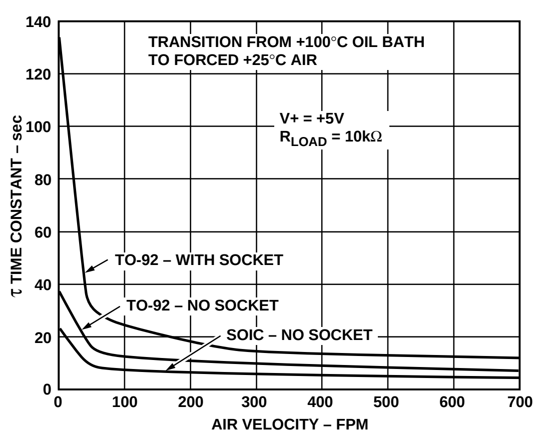


Figure 23. Thermal Time Constant in Forced Air

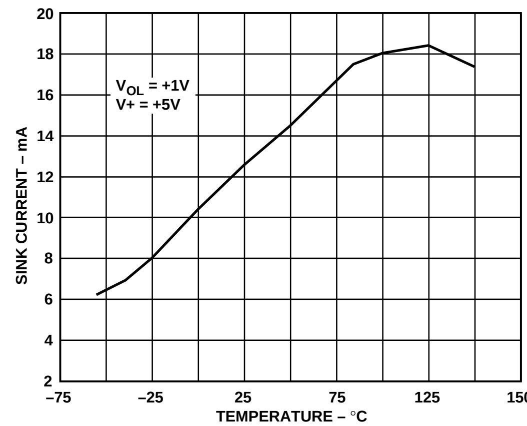


Figure 24. TMP03 Open-Collector Sink Current vs. Temperature

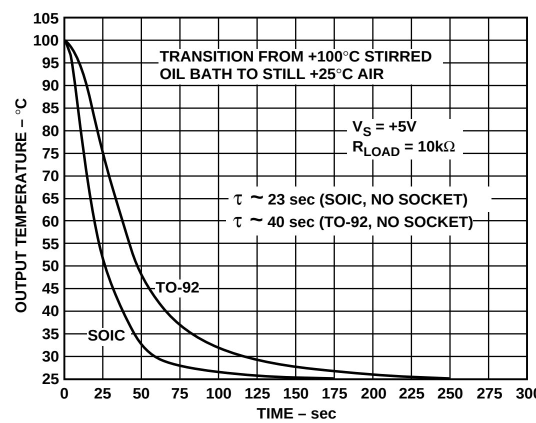


Figure 25. Thermal Response Time in Still Air

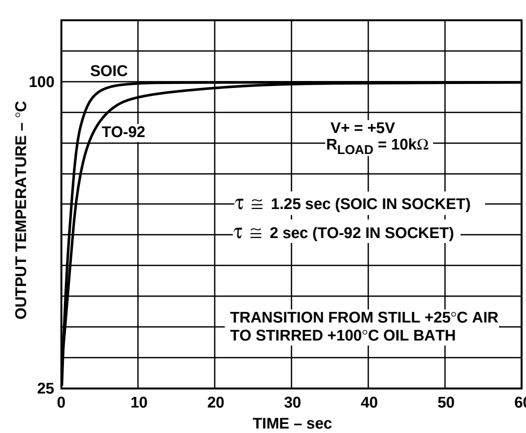


Figure 26. Thermal Response Time in Stirred Oil Bath

APPLICATIONS INFORMATION

Supply Bypassing

Precision analog products, such as the TMP03/TMP04, require a well filtered power source. Since the TMP03/TMP04 operate from a single +5 V supply, it seems convenient to simply tap into the digital logic power supply. Unfortunately, the logic supply is often a switch-mode design, which generates noise in the 20 kHz to 1 MHz range. In addition, fast logic gates can generate glitches hundred of millivolts in amplitude due to wiring resistance and inductance.

If possible, the TMP03/TMP04 should be powered directly from the system power supply. This arrangement, shown in Figure 27, will isolate the analog section from the logic switching transients. Even if a separate power supply trace is not available, however, generous supply bypassing will reduce supply-line induced errors. Local supply bypassing consisting of a 10 μF tantalum electrolytic in parallel with a 0.1 μF ceramic capacitor is recommended (Figure 28a).

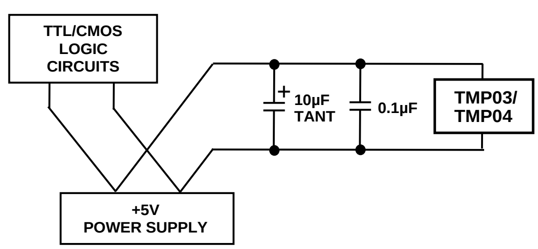
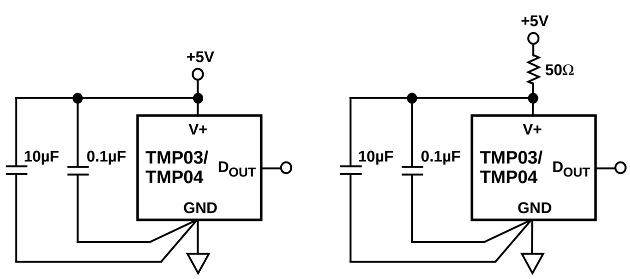


Figure 27. Use Separate Traces to Reduce Power Supply Noise



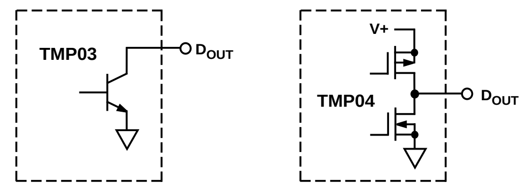
a. *b.*

Figure 28. Recommended Supply Bypassing for the TMP03/TMP04

The quiescent power supply current requirement of the TMP03/TMP04 is typically only 900 μA. The supply current will not change appreciably when driving a light load (such as a CMOS gate), so a simple RC filter can be added to further reduce power supply noise (Figure 28b).

TMP03/TMP04 Output Configurations

The TMP03 (Figure 29a) has an open-collector NPN output which is suitable for driving a high current load, such as an opto-isolator. Since the output source current is set by the pull-up resistor, output capacitance should be minimized in TMP03 applications. Otherwise, unequal rise and fall times will skew the pulse width and introduce measurement errors. The NPN transistor has a breakdown voltage of 18 V.



a. *b.*

Figure 29. TMP03/TMP04 Digital Output Structure

The TMP04 has a "totem-pole" CMOS output (Figure 29b) and provides rail-to-rail output drive for logic interfaces. The rise and fall times of the TMP04 output are closely matched, so that errors caused by capacitive loading are minimized. If load capacitance is large, for example when driving a long cable, an external buffer may improve accuracy. See the "Remote Temperature Measurement" section of this data sheet for suggestions.

Interfacing the TMP03 to Low Voltage Logic

The TMP03's open-collector output is ideal for driving logic gates that operate from low supply voltages, such as 3.3 V. As shown in Figure 30, a pull-up resistor is connected from the low voltage logic supply (2.9 V, 3 V, etc.) to the TMP03 output. Current through the pull-up resistor should be limited to about 1 mA, which will maintain an output LOW logic level of <200 mV.

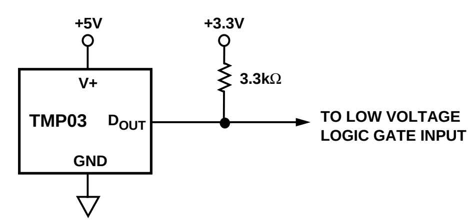
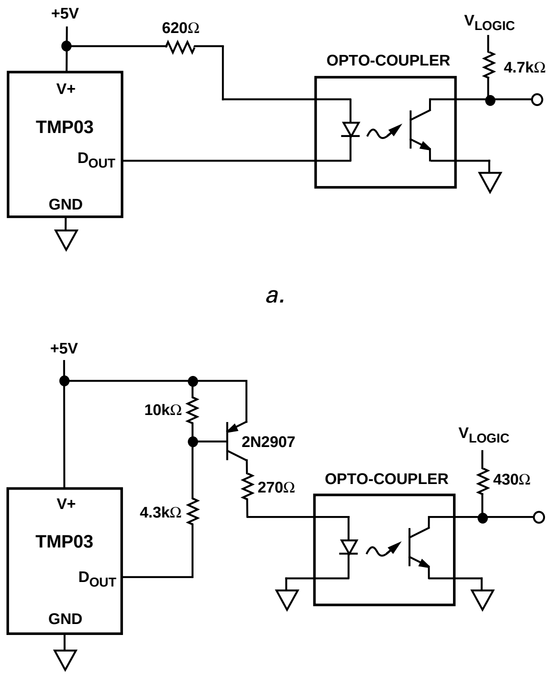


Figure 30. Interfacing to Low Voltage Logic

Remote Temperature Measurement

When measuring a temperature in situations where high common-mode voltages exist, an opto-isolator can be used to isolate the output (Figure 31a). The TMP03 is recommended in this application because its open-collector NPN transistor has a higher current sink capability than the CMOS output of the TMP04. To maintain the integrity of the measurement, the opto-isolator must have relatively equal turn-on and turn-off times. Some Darlington opto-isolators, such as the 4N32, have a turn-off time that is much longer than their turn-on time. In this case, the T1 time will be longer than T2, and an erroneous reading will result. A PNP transistor can be used to provide greater current drive to the opto-isolator (Figure 31b). An opto-isolator with an integral logic gate output, such as the H11L1 from Quality Technology, can also be used (Figure 32).



b.

Figure 31. Optically Isolating the Digital Output

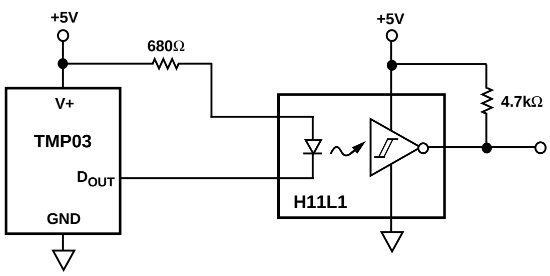


Figure 32. An Opto-Isolator with Schmitt Trigger Logic Gate Improves Output Rise and Fall Times

The TMP03 and TMP04 are superior to analog-output transducers for measuring temperature at remote locations, because the digital output provides better noise immunity than an analog signal. When measuring temperature at a remote location, the ratio of the output pulses must be maintained. To maintain the integrity of the pulse width, an external buffer can be added. For example, adding a differential line driver such as the ADM485 permits precise temperature measurements at distances up to 4000 ft. (Figure 33). The ADM485 driver and receiver skew is only 5 ns maximum, so the TMP04 duty cycle is not degraded. Up to 32 ADM485s can be multiplexed onto one line by providing additional decoding.

As previously mentioned, the digital output of the TMP03/TMP04 provides excellent noise immunity in remote measurement applications. The user should be aware, however, that heat from an external cable can be conducted back to the TMP03/TMP04. This heat conduction through the connecting wires can influence the temperature of the TMP03/TMP04. If large temperature differences exist within the sensor environment, an opto-isolator, level shifter or other thermal barrier can be used to minimize measurement errors.

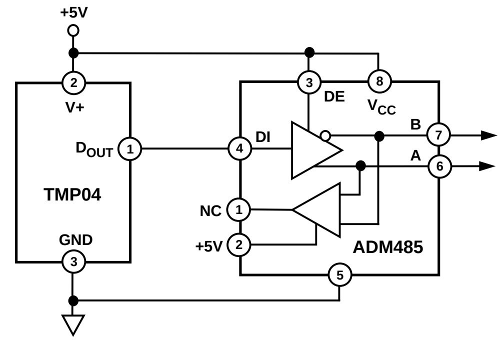


Figure 33. A Differential Line Driver for Remote Temperature Measurement

Microcomputer Interfaces

The TMP03/TMP04 output is easily decoded with a microcomputer. The microcomputer simply measures the T1 and T2 periods in software or hardware, and then calculates the temperature using the equation in the Output Encoding section of this data sheet (page 4). Since the TMP03/TMP04's output is ratiometric, precise control of the counting frequency is not required. The only timing requirements are that the clock frequency be high enough to provide the required measurement resolution (see the Output Encoding section for details) and that the clock source be stable. The ratiometric output of the TMP03/TMP04 is an advantage because the microcomputer's crystal clock frequency is often dictated by the serial baud rate or other timing considerations.

Pulse width timing is usually done with the microcomputer's on-chip timer. A typical example, using the 80C51, is shown in Figure 34. This circuit requires only one input pin on the microcomputer, which highlights the efficiency of the TMP04's pulse width output format. Traditional serial input protocols, with data line, clock and chip select, usually require three or more I/O pins.

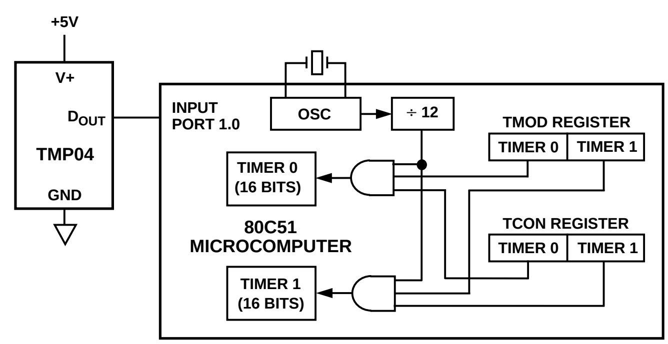


Figure 34. A TMP04 Interface to the 80C51 Microcomputer

The 80C51 has two 16-bit timers. The clock source for the timers is the crystal oscillator frequency divided by 12. Thus, a crystal frequency of 12 MHz or greater will provide resolution of 1 µs or less.

The 80C51 timers are controlled by two dedicated registers. The TMOD register controls the timer mode of operation, while TCON controls the start and stop times. Both the TMOD and TCON registers must be set to start the timer.

Software for the interface is shown in Listing 1. The program monitors the TMP04 output, and turns the counters on and off to measure the duty cycle. The time that the output is high is measured by Timer 0, and the time that the output is low is measured by Timer 1. When the routine finishes, the results are available in Special Function Registers (SFRs) 08AH through 08DH.

Listing 1. An 80C51 Software Routine for the TMP04

```
;
;  Test of a TMP04 interface to the 8051,
;  using timer 0 and timer 1 to measure the duty cycle
;
;  This program has three steps:
;   1. Clear the timer registers, then wait for a low-to-
;      high transition on input P1.0 (which is connected
;      to the output of the TMP04).
;   2. When P1.0 goes high, timer 0 starts. The program
;      then loops, testing P1.0.
;   3. When P1.0 goes low, timer 0 stops & timer 1 starts. The
;      program loops until P1.0 goes low, when timer 1 stops
;      and the TMP04's T1 and T2 values are stored in Special
;      Function registers 8AH through 8DH (TL0 through TH1).
;
;
;  Primary controls
$MOD51
$TITLE(TMP04 Interface, Using T0 and T1)
$PAGEWIDTH(80)
$DEBUG
$OBJECT
;
;  Variable declarations
;
PORT1           DATA      90H                   ;SFR register for port 1
;TCON           DATA      88H                   ;timer control
;TMOD           DATA      89H                   ;timer mode
;TH0            DATA      8CH                   ;timer 0 hi byte
;TH1            DATA      8DH                   ;timer 1 hi byte
;TL0            DATA      8AH                   ;timer 0 lo byte
;TL1            DATA      8BH                   ;timer 1 low byte
;
;
                ORG       100H                  ;arbitrary start
;
READ_TMP04:     MOV       A,#00                 ;clear the
                MOV       TH0,A                 ; counters
                MOV       TH1,A                 ;  first
                MOV       TL0,A                 ;
                MOV       TL1,A                 ;
WAIT_LO:        JB        PORT1.0,WAIT_LO       ;wait for TMP04 output to go low
                MOV       A,#11H                ;get ready to start timer0
                MOV       TMOD,A
WAIT_HI:        JNB       PORT1.0,WAIT_HI       ;wait for output to go high
;
;Timer 0 runs while TMP04 output is high
;
                SETB      TCON.4                ;start timer 0
WAITTIMER0:     JB        PORT1.0,WAITTIMER0
                CLR       TCON.4                ;shut off timer 0
;
;Timer 1 runs while TMP04 output is low
;
                SETB      TCON.6                ;start timer 1
WAITTIMER1:     JNB       PORT1.0,WAITTIMER1
                CLR       TCON.6                ;stop timer 1
                MOV       A,#0H                 ;get ready to disable timers
                MOV       TMOD,A
                RET
                END
```

When the READ_TMP04 routine is called, the counter registers are cleared. The program sets the counters to their 16-bit mode, and then waits for the TMP04 output to go high. When the input port returns a logic high level, Timer 0 starts. The timer continues to run while the program monitors the input port. When the TMP04 output goes low, Timer 0 stops and Timer 1 starts. Timer 1 runs until the TMP04 output goes high, at which time the TMP04 interface is complete. When the subroutine ends, the timer values are stored in their respective SFRs and the TMP04's temperature can be calculated in software.

Since the 80C51 operates asynchronously to the TMP04, there is a delay between the TMP04 output transition and the start of the timer. This delay can vary between 0 µs and the execution time of the instruction that recognized the transition. The 80C51's "jump on port.bit" instructions (JB and JNB) require 24 clock cycles for execution. With a 12 MHz clock, this produces an uncertainty of 2 µs (24 clock cycles/12 MHz) at each transition of the TMP04 output. The worst case condition occurs when T1 is 4 µs shorter than the actual value and T2 is 4 µs longer. For a +25°C reading ("room temperature"), the nominal error caused by the 2 µs delay is only about ±0.15°C.

The TMP04 is also easily interfaced to digital signal processors (DSPs), such as the ADSP-210x series. Again, only a single I/O pin is required for the interface (Figure 35).

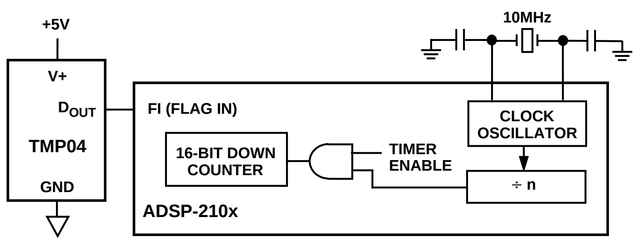


Figure 35. Interfacing the TMP04 to the ADSP-210x Digital Signal Processor

The ADSP-2101 only has one counter, so the interface software differs somewhat from the 80C51 example. The lack of two counters is not a limitation, however, because the DSP architecture provides very high execution speed. The ADSP-2101 executes one instruction for each clock cycle, versus one instruction for twelve clock cycles in the 80C51, so the ADSP-2101 actually produces a more accurate conversion while using a lower oscillator frequency.

The timer of the ADSP-2101 is implemented as a down counter. When enabled by means of a software instruction, the counter is decremented at the clock rate divided by a programmable prescaler. Loading the value $n - 1$ into the prescaler register will divide the crystal oscillator frequency by n. For the circuit of Figure 35, therefore, loading 4 into the prescaler will divide the 10 MHz crystal oscillator by 5 and thereby decrement the counter at a 2 MHz rate. The TMP04 output is ratiometric, of course, so the exact clock frequency is not important.

A typical software routine for interfacing the TMP04 to the ADSP-2101 is shown in Listing 2. The program begins by initializing the prescaler and loading the counter with $0FFFF_H$. The ADSP-2101 monitors the FI flag input to establish the falling edge of the TMP04 output, and starts the counter. When the TMP04 output goes high, the counter is stopped. The counter value is then subtracted from $0FFFF_H$ to obtain the actual number of counts, and the count is saved. Then the counter is reloaded and runs until the TMP04 output goes low. Finally, the TMP04 pulse widths are converted to temperature using the scale factor of Equation 1.

Some applications may require a hardware interface for the TMP04. One such application could be to monitor the temperature of a high power microprocessor. The TMP04 interface would be included as part of the system ASIC, so that the microprocessor would not be burdened with the overhead of timing the output pulse widths.

A typical hardware interface for the TMP04 is shown in Figure 36. The circuit measures the output pulse widths with a resolution of ±1 µs. The TMP04 T1 and T2 periods are measured with two cascaded 74HC4520 8-bit counters. The counters, accumulating clock pulses from the 1 MHz external oscillator, have a maximum period of 65 ms.

The logic interface is straightforward. On both the rising and falling edges of the TMP04 output, an exclusive-or gate generates a pulse. This pulse triggers one half of a 74HC4538 dual one-shot. The pulse from the one-shot is ANDed with the TMP04 output polarity to store the counter contents in the appropriate output registers. The falling edge of this pulse also triggers the second one-shot, which generates a reset pulse for the counters. After the reset pulse, the counters will begin to count the next TMP04 output phase.

As previously mentioned, the counters have a maximum period of 65 ms with a 1 MHz clock input. However, the TMP04's T1 and T2 times will never exceed 32 ms. Therefore the most significant bit (MSB) of counter #2 will not go high in normal operation, and can be used to warn the system that an error condition (such as a broken connection to the TMP04) exists.

The circuit of Figure 36 will latch and save both the T1 and T2 times simultaneously. This makes the circuit suitable for debugging or test purposes as well as for a general purpose hardware interface. In a typical ASIC application, of course, one set of latches could be eliminated if the latch contents, and the output polarity, were read before the next phase reversal of the TMP04.

Listing 2. Software Routine for the TMP04-to-ADSP-210x Interface

```
;
{ ADSP-21XX Temperature Measurement Routine           TEMPERAT.DSP

      Altered Registers:          ax0, ay0, af, ar,
                                  si, sr0,
                                  my0, mr0, mr1, mr2.
      Return value:               ar –> temperature result in 14.2 format
      Computation time:           2 * TMP04 output period
}
.MODULE/RAM/BOOT=0    TEMPERAT;            { Beginning TEMPERAT Program }
.ENTRY TEMPMEAS;                           { Entry point of this subroutine }
.CONST PRESCALER=4;
.CONST TIMFULSCALE=0Xffff;
TEMPMEAS:     si=PRESCALER;                { For timer prescaler }
              sr0=TIMFULSCALE;             { Timer counter full scale }
              dm(0x3FFB)=si;               { Timer Prescaler set up to 5 }
              si=TIMFULSCALE;              { CLKin=10MHz,Timer Period=32.768ms }
              dm(0x3FFC)=si;               { Timer Counter Register to 65535 }
              dm(0x3FFD)=si;               { Timer Period Register to 65535 }
              imask=0x01;                  { Unmask Interrupt timer }
TEST1:        if not fi jump TEST1;           { Check for FI=1 }
TEST0:        if fi jump TEST0;            { Check for FI=0 to locate transition }
              ena timer;                   { Enable timer, count at a 500ns rate }
COUNT2:       if not fi jump COUNT2;       { Check for FI=1 to stop count }
              dis timer;
              ay0=dm(0x3FFC);              { Save counter=T2 in ALU register }
              ar=sr0-ay0;
              ax0=ar;
              dm(0x3FFC)=si;               { Reload counter at full scale }
              ena timer;
COUNT1:       if fi jump COUNT1;           { Check for FI=0 to stop count }
              dis timer;
              ay0=dm(0x3FFC);              { Save counter=T1 in ALU register }
              ar=sr0-ay0;
              my0=400;
              mr=ar*my0(uu);               { mr=400*T1 }
              ay0=mr0;                     { af=MSW of dividend, ay0=LSW }
              ar=mr1; af=pass ar;          { ax0=16-bit divisor }
COMPUTE:      astat=0;                     { To clear AQ flag }
              divq ax0; divq ax0;          { Division 400*T1/T2 }
              divq ax0; divq ax0;          { with 0.3 < T1/T2 < 0.7 }
              divq ax0; divq ax0;
              divq ax0; divq ax0;
              divq ax0; divq ax0;
              divq ax0; divq ax0;
              divq ax0; divq ax0;
              divq ax0; divq ax0;
              divq ax0; divq ax0;          { Result in ay0 }
              ax0=0x03AC;                  { ax0=235*4 }
              ar=ax0-ay0;                  { ar=235-400*T1/T2, result in øC }
              rts;                         { format 14.2 }
.ENDMOD;                                   { End of the subprogram }
```

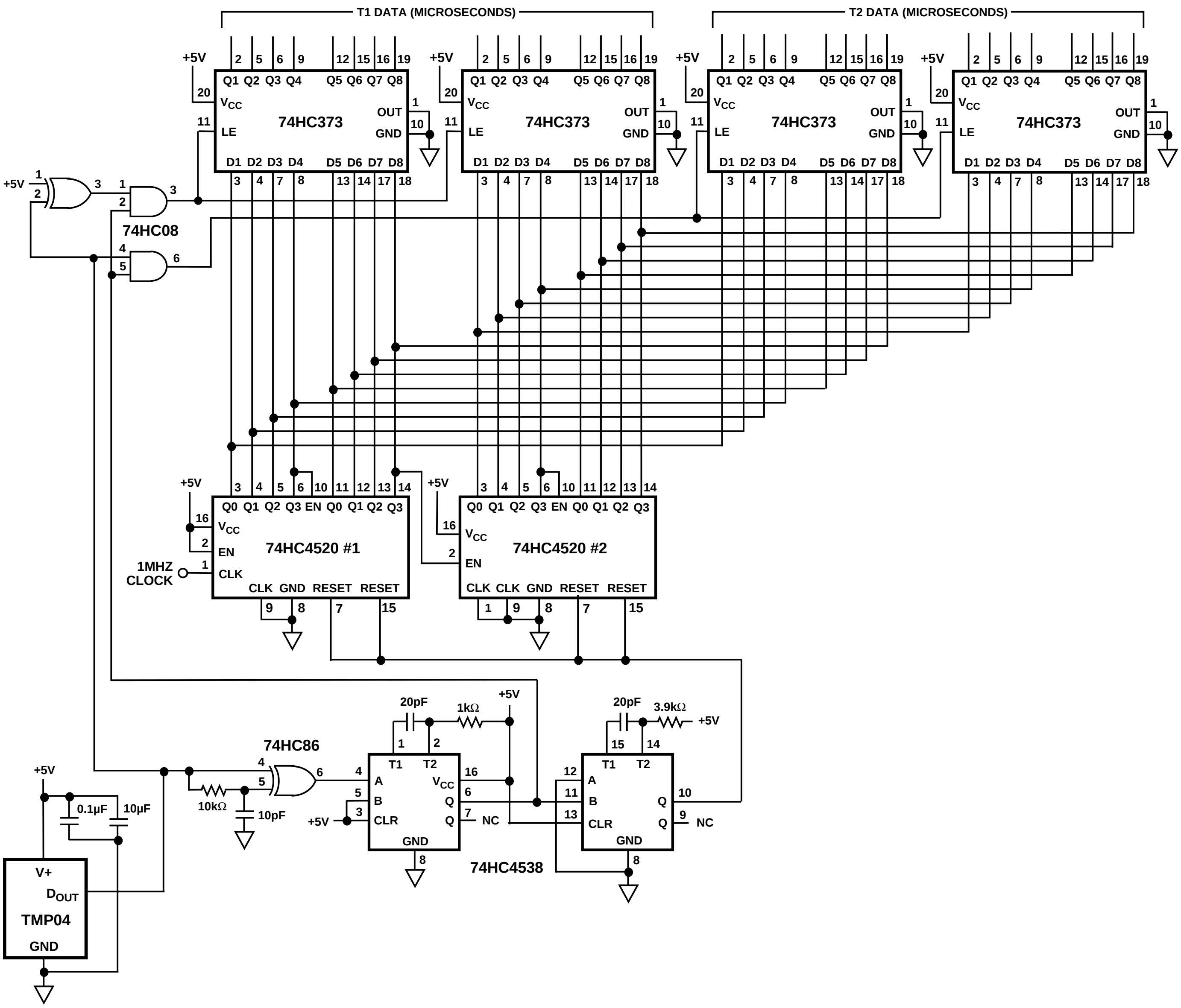


Figure 36. A Hardware Interface for the TMP04

Monitoring Electronic Equipment

The TMP03/TMP04 are ideal for monitoring the thermal environment within electronic equipment. For example, the surface mounted package will accurately reflect the exact thermal conditions which affect nearby integrated circuits. The TO-92 package, on the other hand, can be mounted above the surface of the board, to measure the temperature of the air flowing over the board.

The TMP03 and TMP04 measure and convert the temperature at the surface of their own semiconductor chip. When the TMP03/TMP04 are used to measure the temperature of a nearby heat source, the thermal impedance between the heat source and the TMP03/TMP04 must be considered. Often, a thermocouple or other temperature sensor is used to measure the temperature of the source while the TMP03/TMP04 temperature is monitored by measuring T1 and T2. Once the thermal impedance is determined, the temperature of the heat source can be inferred from the TMP03/TMP04 output.

One example of using the TMP04 to monitor a high power dissipation microprocessor or other IC is shown in Figure 37. The TMP04, in a surface mount package, is mounted directly beneath the microprocessor's pin grid array (PGA) package. In a typical application, the TMP04's output would be connected to an ASIC where the pulse width would be measured (see the Hardware Interface section of this data sheet for a typical interface schematic). The TMP04 pulse output provides a significant advantage in this application because it produces a linear temperature output while needing only one I/O pin and without requiring an A/D converter.

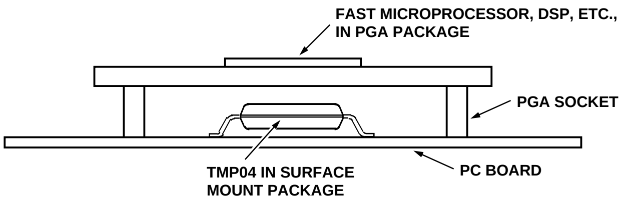


Figure 37. Monitoring the Temperature of a High Power Microprocessor Improves System Reliability

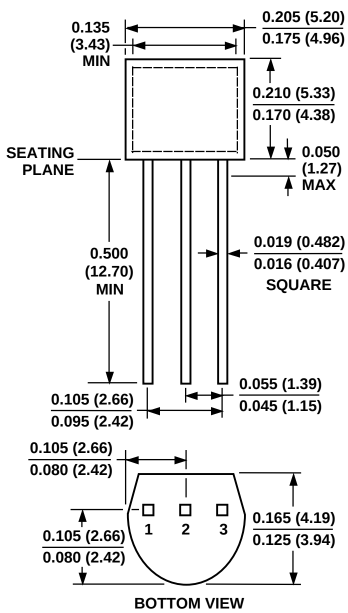
Thermal Response Time

The time required for a temperature sensor to settle to a specified accuracy is a function of the thermal mass of, and the thermal conductivity between, the sensor and the object being sensed. Thermal mass is often considered equivalent to capacitance. Thermal conductivity is commonly specified using the symbol Θ, and can be thought of as thermal resistance. It is commonly specified in units of degrees per watt of power transferred across the thermal joint. Thus, the time required for the TMP03/TMP04 to settle to the desired accuracy is dependent on the package selected, the thermal contact established in that particular application, and the equivalent power of the heat source. In most applications, the settling time is probably best determined empirically. The TMP03/TMP04 output operates at a nominal frequency of 35 Hz at +25°C, so the minimum settling time resolution is 27 ms.

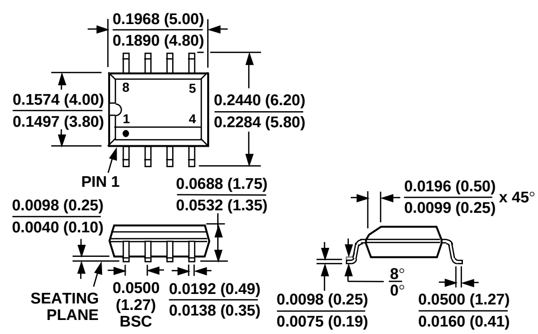
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

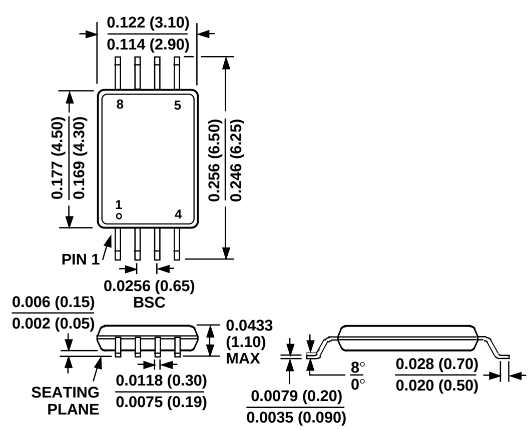
3-Pin TO-92



8-Pin SOIC (SO-8)



8-Pin TSSOP (RU-8)



C2063–18–9/95

PRINTED IN U.S.A.

ANALOG DEVICES

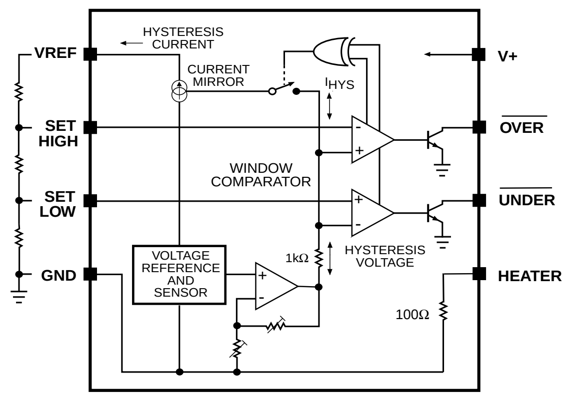
Airflow and Temperature Sensor

TMP12*

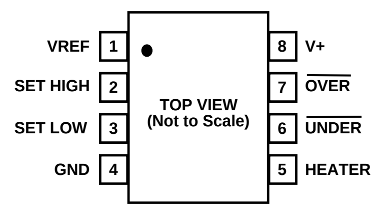
FEATURES
Temperature Sensor Includes 100 Ω Heater
Heater Provides Power IC Emulation
Accuracy ±3°C typ. from −40°C to +100°C
Operation to +150°C
5 mV/°C Internal Scale-Factor
Resistor Programmable Temperature Setpoints
20 mA Open-Collector Setpoint Outputs
Programmable Thermal Hysteresis
Internal 2.5 V Reference
Single 5 V Operation
400 μA Quiescent Current (Heater OFF)
Minimal External Components

APPLICATIONS
System Airflow Sensor
Equipment Over-Temperature Sensor
Over-Temperature Protection
Power Supply Thermal Sensor
Low-Cost Fan Controller

FUNCTIONAL BLOCK DIAGRAM



PINOUTS
DIP And SO



GENERAL DESCRIPTION

The TMP12 is a silicon-based airflow and temperature sensor designed to be placed in the same airstream as heat generating components that require cooling. Fan cooling may be required continuously, or during peak power demands, e.g. for a power supply, and if the cooling systems fails, system reliability and/or safety may be impaired. By monitoring temperature while emulating a power IC, the TMP12 can provide a warning of cooling system failure.

The TMP12 generates an internal voltage that is linearly proportional to Celsius (Centigrade) temperature, nominally +5 mV/°C. The linearized output is compared with voltages from an external resistive divider connected to the TMP12's 2.5 V precision reference. The divider sets up one or two reference voltages, as required by the user, providing one or two temperature setpoints. Comparator outputs are open-collector transistors able to sink over 20 mA. There is an on-board hysteresis generator provided to speed up the temperature-setpoint output transitions, this also reduces erratic output transitions in noisy environments. Hysteresis is programmed by the external resistor chain and is determined by the total current drawn from the 2.5 V reference. The TMP12 airflow sensor also incorporates a precision, low temperature coefficient 100 Ω heater resistor that may be connected directly to an external 5 V supply. When the heater is activated it raises the die temperature in the DIP package approximately 20°C above ambient (in still air). The purpose of the heater in the TMP12 is to emulate a power IC, such as a regulator or Pentium CPU which has a high internal dissipation.

When subjected to a fast airflow, the package and die temperatures of the power device and the TMP12 (if located in the same airstream) will be reduced by an amount proportional to the rate of airflow. The internal temperature rise of the TMP12 may be reduced by placing a resistor in series with the heater, or reducing the heater voltage.

The TMP12 is intended for single 5 V supply operation, but will operate on a 12 V supply. The heater is designed to operate from 5 V only. Specified temperature range is from −40°C to +125°C, operation extends to +150°C at 5 V with reduced accuracy.

The TMP12 is available in 8-pin plastic DIP and SO packages.

***Protected by U.S. Patent No. 5,195,827.**

REV. 0

One Technology Way, P.O. Box 9106, Norwood. MA 02062-9106, U.S.A.
Tel: 617/329-4700 Fax: 617/326-8703

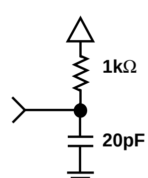
TMP12–SPECIFICATIONS (V_S = +5 V, −40°C ≤ T_A ≤ +125°C unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
ACCURACY						
Accuracy (High, Low Setpoints)		T_A = +25°C		±2	±3	°C
Accuracy (High, Low Setpoints)		T_A = −40°C to +100°C		±3	±5	°C
Internal Scale Factor		T_A = −40°C to +100°C	+4.9	+5	+5.1	mV/°C
Power Supply Rejection Ratio	PSRR	4.5 V ≤ +V_S ≤ 5.5 V		0.1	0.5	°C/V
Linearity		T_A = −40°C to +125°C		0.5		°C
Repeatability		T_A = −40°C to +125°C		0.3		°C
Long Term Stability		T_A = +125°C for 1 k Hrs		0.3		°C
SETPOINT INPUTS						
Offset Voltage	V_{OS}			0.25		mV
Output Voltage Drift	TCV_{OS}			3		µV/°C
Input Bias Current	I_B			25	100	nA
VREF OUTPUT						
Output Voltage	VREF	T_A = +25°C, No Load	2.49	2.50	2.51	V
Output Voltage	VREF	T_A = −40°C to +100°C, No Load		2.5 ±0.015		V
Output Drift	TC_{VREF}			−10		ppm/°C
Output Current, Zero Hysteresis	I_{VREF}			7		µA
Hysteresis Current Scale Factor	SF_{HYS}			5		µA/°C
OPEN-COLLECTOR OUTPUTS						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA		0.25	0.4	V
Output Low Voltage	V_{OL}	I_{SINK} = 20 mA		0.6		V
Output Leakage Current	I_{OH}	V_S = 12 V		1	100	µA
Fall Time	t_{HL}	See Test Load		40		ns
HEATER						
Resistance	R_H	T_A = +25°C	97	100	103	Ω
Temperature Coefficient		T_A = −40°C to +125°C		100		ppm/°C
Maximum Continuous Current	I_H	See Note 1			60	mA
POWER SUPPLY						
Supply Range	+V_S		4.5		5.5	V
Supply Current	I_{SY}	Unloaded at +5 V		400	600	µA
	I_{SY}	Unloaded at +12 V[2]		450		µA

NOTES
[1]Guaranteed but not tested.
[2]TMP12 is specified for operation from a 5 V supply. However, operation is allowed up to a 12 V supply, but not tested at 12 V. Maximum heater supply is 6 V.

Specifications subject to change without notice.

TEST LOAD



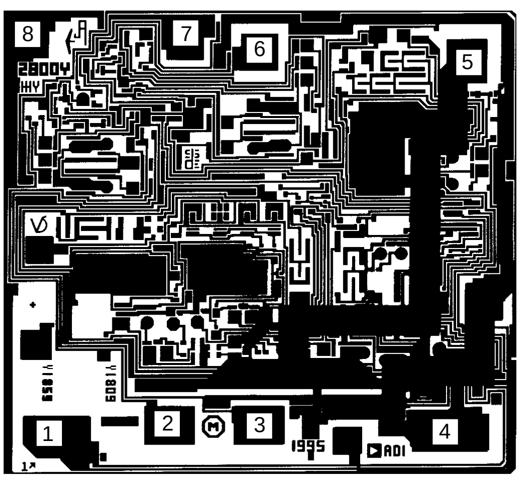
WAFER TEST LIMITS (V_S = +5 V, GND = 0 V, T_A = +25°C, unless otherwise noted.)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
ACCURACY						
Accuracy (High, Low Setpoints)		T_A = +25°C			±3	°C
Internal Scale Factor		T_A = +25°C	+4.9	+5	+5.1	mV/°C
SETPOINT INPUTS						
Input Bias Current	I_B				100	nA
VREF OUTPUT						
Output Voltage	VREF	T_A = +25°C, No Load	2.49		2.51	V
OPEN-COLLECTOR OUTPUTS						
Output Low Voltage	V_{OL}	I_{SINK} = 1.6 mA			0.4	V
Output Leakage Current	I_{OH}	V_S = 12 V			100	µA
HEATER						
Resistance	R_H	T_A = +25°C	97	100	103	Ω
POWER SUPPLY						
Supply Range	$+V_S$		4.5		5.5	V
Supply Current	I_{SY}	Unloaded at +5 V			600	µA

NOTE
Electrical tests are performed at wafer probe to the limits shown. Due to variations in assembly methods and normal yield loss, yield after packaging is not guaranteed for standard product dice. Consult factory to negotiate specifications based on dice lot qualification through sample lot assembly and testing.

DICE CHARACTERISTICS

Die Size 0.078 × 0.071 inch, 5,538 sq. mils
(1.98 × 1.80 mm, 3.57 sq. mm)
Transistor Count: 105



1. VREF
2. SET HIGH INPUT
3. SET LOW INPUT
4. GND
5. HEATER
6. $\overline{\text{UNDER}}$ OUTPUT
7. $\overline{\text{OVER}}$ OUTPUT
8. V+

For additional DICE ordering information, refer to databook.

CAUTION
ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the TMP12 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

ABSOLUTE MAXIMUM RATINGS*

Supply Voltage . . . . −0.3 V to +15 V
Heater Voltage . . . . +6 V
Setpoint Input Voltage . . . . −0.3 V to [(V+) +0.3 V]
Reference Output Current . . . . 2 mA
Open-Collector Output Current . . . . 50 mA
Open-Collector Output Voltage . . . . +15 V
Operating Temperature Range . . . . −55°C to +150°C
Dice Junction Temperature . . . . +175°C
Storage Temperature Range . . . . −65°C to +160°C
Lead Temperature(Soldering, 60 sec) . . . . +300°C

Package Type	Θ_{JA}	Θ_{JC}	Units
8-Pin Plastic DIP (P)	103[1]	43	°C/W
8-Lead SOIC (S)	158[2]	43	°C/W

NOTES
[1]ΘJA is specified for device in socket (worst case conditions).
[2]ΘJA is specified for device mounted on PCB.

CAUTION

1. Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation at or above this specification is not implied. Exposure to the above maximum rating conditions for extended periods may affect device reliability.
2. Digital inputs and outputs are protected, however, permanent damage may occur on unprotected units from high-energy electrostatic fields. Keep units in conductive foam or packaging at all times until ready to use. Use proper antistatic handling procedures.
3. Remove power before inserting or removing units from their sockets.

ORDERING GUIDE

Model/Grade	Temperature Range[1]	Package Description	Package Option
TMP12FP	XIND	Plastic DIP	N-8
TMP12FS	XIND	SOIC	SO-8
TMP12GBC	+25°C	Die	

NOTE
[1]XIND = −40°C to +125°C

FUNCTIONAL DESCRIPTION

The TMP12 incorporates a heating element, temperature sensor, and two user-selectable setpoint comparators on a single substrate. By generating a known amount of heat, and using the setpoint comparators to monitor the resulting temperature rise, the TMP12 can indirectly monitor the performance of a system's cooling fan.

The TMP12 temperature sensor section consists of a bandgap voltage reference which provides both a constant 2.5 V output and a voltage which is proportional to absolute temperature (VPTAT). The VPTAT has a precise temperature coefficient of 5 mV/K and is 1.49 V (nominal) at +25°C. The comparators compare VPTAT with the externally set temperature trip points and generate an open-collector output signal when one of their respective thresholds has been exceeded.

The heat source for the TMP12 is an on-chip 100 Ω low tempco thin-film resistor. When connected to a 5 V source, this resistor dissipates:

$$P_D = \frac{V^2}{R} = \frac{5^2\ V}{100\ \Omega} = 0.25\ W,$$

which generates a temperature rise of about 32°C in still air for the SO packaged device. With an airflow of 450 feet per minute (FPM), the temperature rise is about 22°C. By selecting a temperature setpoint between these two values, the TMP12 can provide a logic-level indication of problems in the cooling system.

A proprietary, low tempco thin-film resistor process, in conjunction with production laser trimming, enables the TMP12 to provide a temperature accuracy of ±3°C (typ) over the rated temperature range. The open-collector outputs are capable of sinking 20 mA, allowing the TMP12 to drive small control relays directly. Operating from a single +5 V supply, the quiescent current is only 600 µA (max), without the heater resistor current.

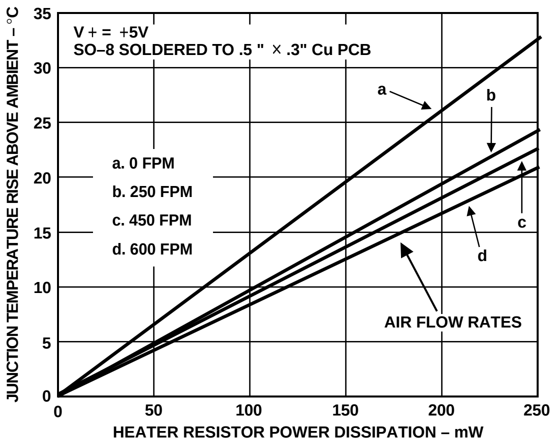


Figure 1. SOIC Junction Temperature Rise vs. Heater Dissipation

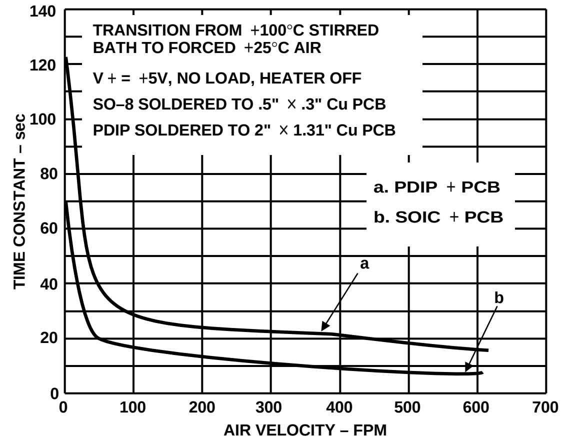


Figure 4. Package Thermal Time Constant in Forced Air

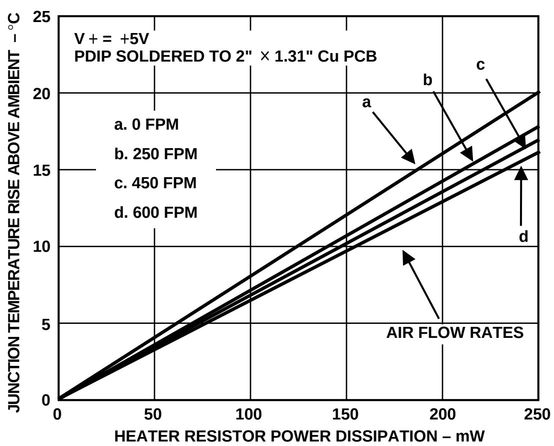


Figure 2. PDIP Junction Temperature Rise vs. Heater Dissipation

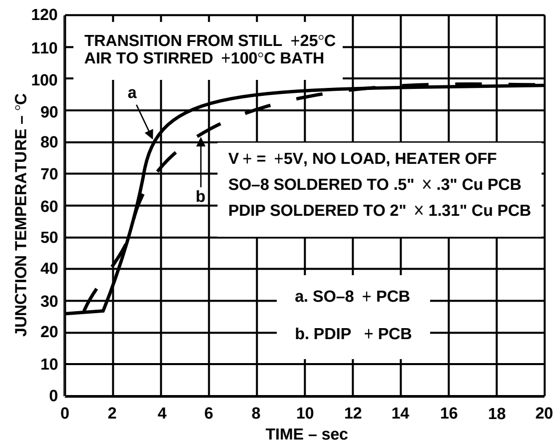


Figure 5. Thermal Response Time in Stirred Oil Bath

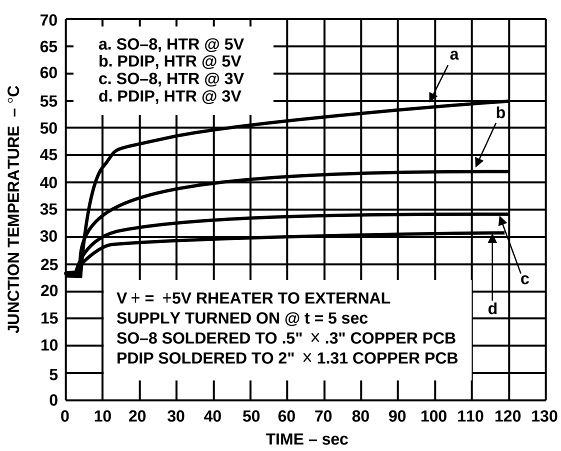


Figure 3. Junction Temperature Rise in Still Air

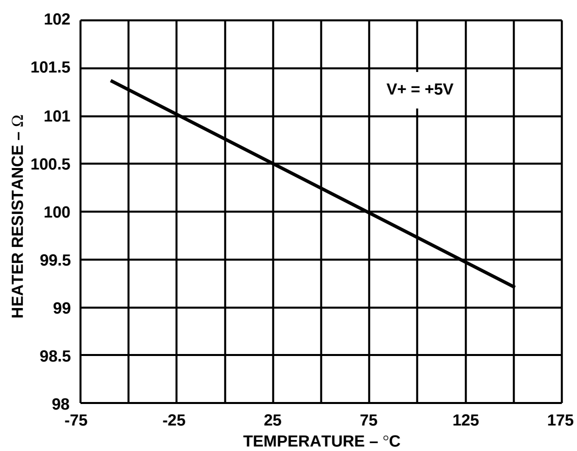


Figure 6. Heater Resistance vs. Temperature

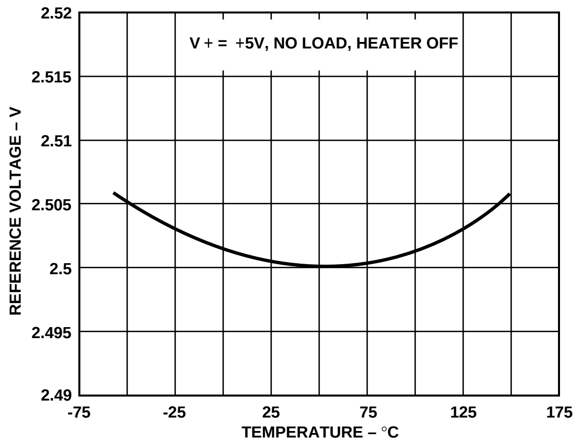


Figure 7. Reference Voltage vs. Temperature

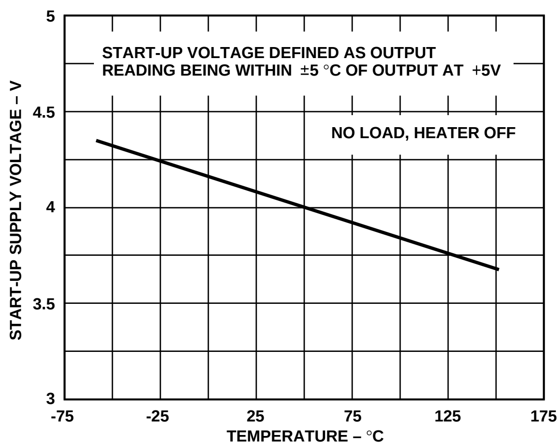


Figure 8. Start-up Voltage vs. Temperature

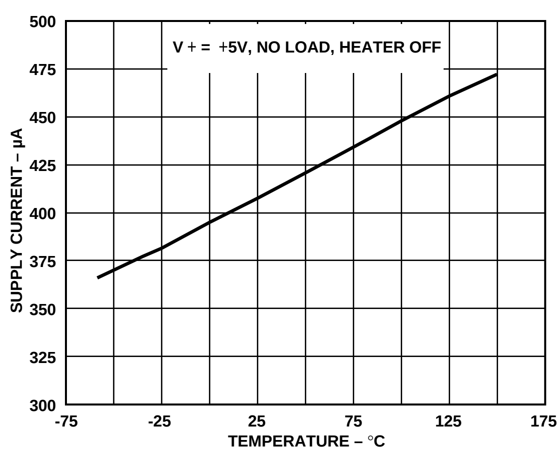


Figure 9. Supply Current vs. Temperature

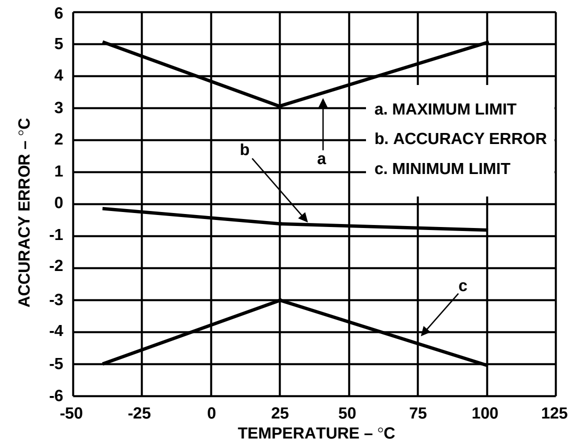


Figure 10. Accuracy Error vs. Temperature

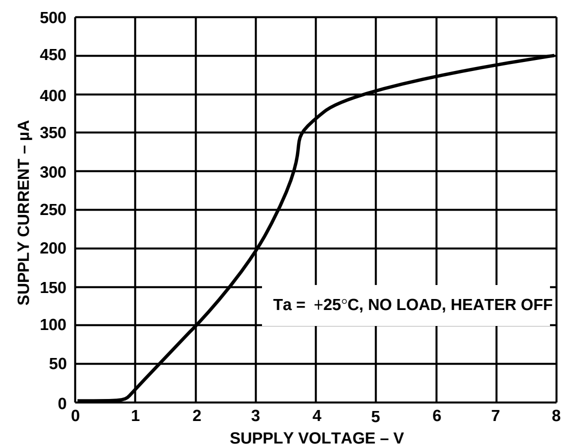


Figure 11. Supply Current vs. Supply Voltage

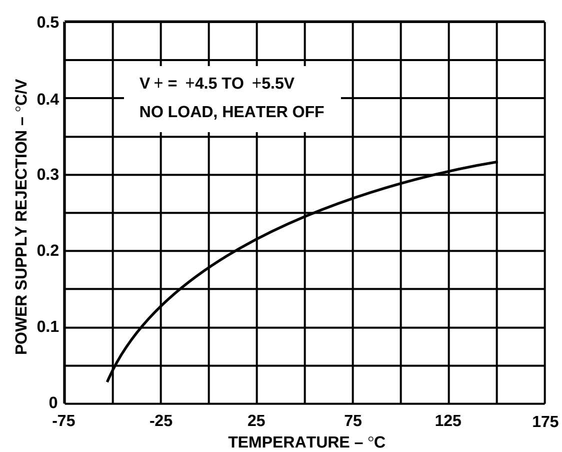


Figure 12. VPTAT Power Supply Rejection vs. Temperature

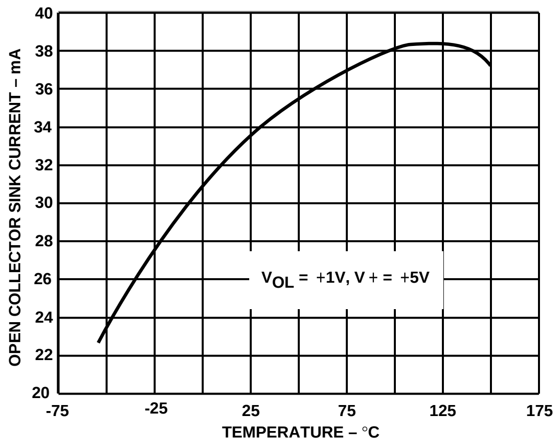


Figure 13. Open-Collector Output Sink Current vs. Temperature

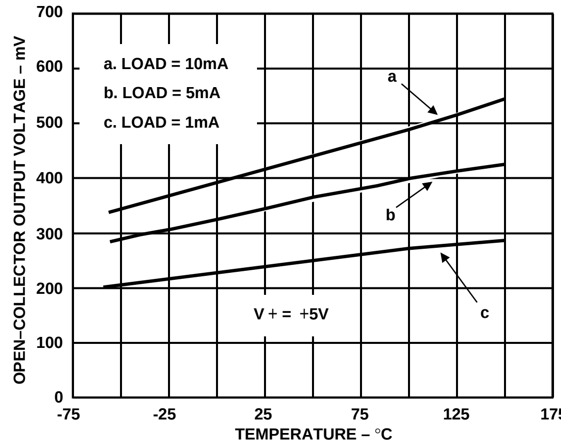


Figure 14. Open-Collector Voltage vs. Temperature

APPLICATIONS INFORMATION

A typical application for the TMP12 is shown in Figure 15. The TMP12 package is placed in the same cooling airflow as a high-power dissipation IC. The TMP12's internal resistor produces a temperature rise which is proportional to air flow, as shown in Figure 16. Any interruption in the airflow will produce an additional temperature rise. When the TMP12 chip temperature exceeds a user-defined setpoint limit, the system controller can take corrective action, such as: reducing clock frequency, shutting down unneeded peripherals, turning on additional fan cooling, or shutting down the system.

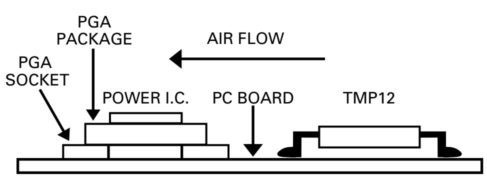


Figure 15. Typical Application

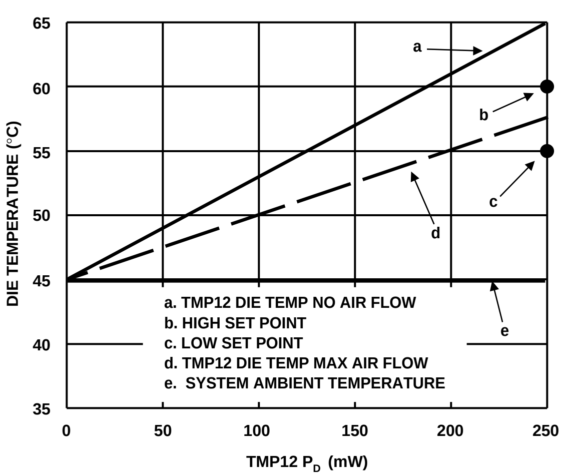


Figure 16. Choosing Temperature Setpoints

Temperature Hysteresis

The temperature hysteresis at each setpoint is the number of degrees beyond the original setpoint temperature that must be sensed by the TMP12 before the setpoint comparator will be reset and the output disabled. Hysteresis prevents "chatter" and "motorboating" in feedback control systems. For monitoring temperature in computer systems, hysteresis prevents multiple interrupts to the CPU which can reduce system performance.

Figure 17 shows the TMP12's hysteresis profile. The hysteresis is programmed, by the user, by setting a specific load current on the reference voltage output VREF. This output current, I_{REF}, is also called the hysteresis current. I_{REF} is mirrored internally by the TMP12, as shown in the functional block diagram, and fed to a buffer with an analog switch.

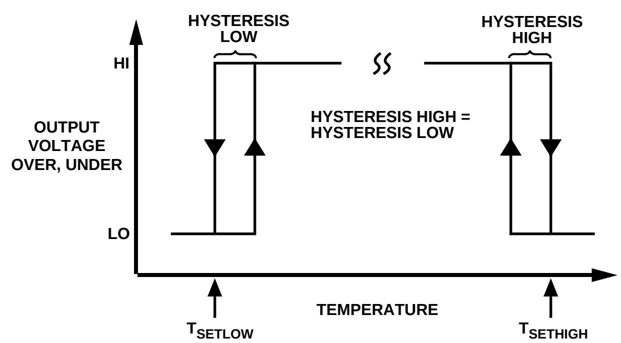


Figure 17. TMP12 Hysteresis Profile

After a temperature setpoint has been exceeded and a comparator tripped, the hysteresis buffer output is enabled. The result is a current of the appropriate polarity which generates a hysteresis offset voltage across an internal 1 kΩ resistor at the comparator input. The comparator output remains "on" until the voltage at the comparator input, now equal to the temperature sensor voltage VPTAT summed with the hysteresis effect, has returned to the programmed setpoint voltage. The comparator then returns

LOW, deactivating the open-collector output and disabling the hysteresis current buffer output. The scale factor for the programmed hysteresis current is:

$$I = I_{VREF} = 5\ \mu A/°C + 7\ \mu A$$

Thus, since VREF = 2.5 V, a reference load resistance of 357 kΩ or greater (output current of 7 µA or less) will produce a temperature setpoint hysteresis of zero degrees. For more details, see the temperature programming discussion below. Larger values of load resistance will only decrease the output current below 7 µA, but will have no effect on the operation of the device. The amount of hysteresis is determined by selecting an appropriate value of load resistance for VREF, as shown below.

Programming the TMP12

The basic thermal monitoring application only requires a simple three-resistor ladder voltage divider to set the high and low setpoints and the hysteresis. These resistors are programmed in the following sequence:

1. Select the desired hysteresis temperature.
2. Calculate the hysteresis current, I_{VREF}
3. Select the desired setpoint temperatures.
4. Calculate the individual resistor divider ladder values needed to develop the desired comparator setpoint voltages at the Set High and Set Low inputs.

The hysteresis current is readily calculated, as shown above. For example, to produce 2 degrees of hysteresis I_{VREF} should be set to 17 µA. Next, the setpoint voltages $V_{SETHIGH}$ and V_{SETLOW} are determined using the VPTAT scale factor of 5 mV/K = 5 mV/(°C + 273.15), which is 1.49 V for +25°C. Finally, the divider resistors are calculated, based on the setpoint voltages.

The setpoint voltages are calculated from the equation:

$$V_{SET} = (T_{SET} + 273.15)(5\ mV/°C)$$

This equation is used to calculate both the $V_{SETHIGH}$ and the V_{SETLOW} values. A simple 3-resistor network, as shown in Figure 18, determines the setpoints and hysteresis value. The equations used to calculate the resistors are:

$$R1\ (k\Omega) = (V_{REF} - V_{SETHIGH})/I_{VREF} = (2.5\ V - V_{SETHIGH})/I_{VREF}$$

$$R2\ (k\Omega) = (V_{SETHIGH} - V_{SETLOW})/I_{VREF}$$

$$R3\ (k\Omega) = V_{SETLOW}/I_{VREF}$$

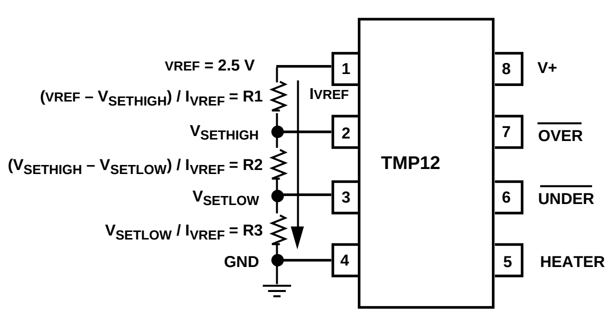


Figure 18. TMP12 Setpoint Programming

For example, setting the high setpoint for +80°C, the low setpoint for +55°C, and hysteresis for 3°C produces the following values:

$$I_{HYS} = I_{VREF} = (3°C \times 5\ \mu A/°C) + 7\ \mu A = 15\ \mu A + 7\ \mu A = 22\ \mu A$$

$$V_{SETHIGH} = (T_{SETHIGH} + 273.15)(5\ mV/°C) = (80°C + 273.15)(5\ mV/°C) = 1.766\ V$$

$$V_{SETLOW} = (T_{SETLOW} + 273.15)(5\ mV/°C) = (55°C + 273.15)(5\ mV/°C) = 1.641\ V$$

$$R1\ (k\Omega) = (VREF - V_{SETHIGH})/I_{VREF} = (2.5\ V - 1.766\ V)/22\ \mu A = 33.36\ k\Omega$$

$$R2\ (k\Omega) = (V_{SETHIGH} - V_{SETLOW})/I_{VREF} = (1.766\ V - 1.641\ V)/22\ \mu A = 5.682\ k\Omega$$

$$R3\ (k\Omega) = V_{SETLOW}/I_{VREF} = (1.641\ V)/22\ \mu A = 74.59\ k\Omega$$

The total of R1 + R2 + R3 is equal to the load resistance needed to draw the desired hysteresis current from the reference, or I_{VREF}.

The nomograph of Figure 19 provides an easy method of determining the correct VPTAT voltage for any temperature. Simply locate the desired temperature on the appropriate scale (K, °C or °F) and read the corresponding VPTAT value from the bottom scale.

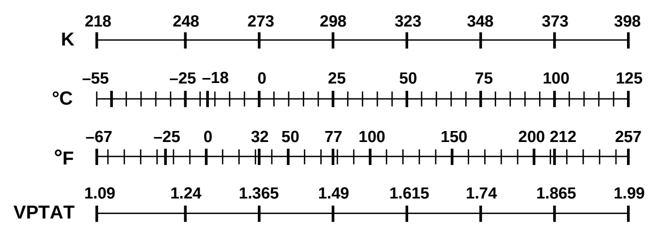


Figure 19. Temperature – VPTAT Scale

The formulas shown above are also helpful in understanding the calculations of temperature setpoint voltages in circuits other than the standard two-temperature thermal/airflow monitor. If a setpoint function is not needed, the appropriate comparator input should be disabled. SETHIGH can be disabled by tying it to V+ or VREF, SETLOW by tying it to GND. Either output can be left disconnected.

Selecting Setpoints

Choosing the temperature setpoints for a given system is an empirical process, because of the wide variety of thermal issues in any practical design. The specific setpoints are dependent on such factors as airflow velocity in the system, adjacent component location and size, PCB thickness, location of copper ground planes, and thermal limits of the system.

The TMP12's temperature rise above ambient is proportional to airflow (Figures 1, 2 and 16). As a starting point, the low setpoint temperature could be set at the system ambient temperature (inside the enclosure) plus one half of the temperature rise above ambient (at the actual airflow in the system). With this setting, the low limit will provide a warning either if the fan output is reduced or if the ambient temperature rises (for example, if the fan's cool air intake is blocked). The high setpoint could then be set for the maximum system temperature to provide a final system shutdown control.

Measuring the TMP12 Internal Temperature

As previously mentioned, the TMP12’s VPTAT generator represents the chip temperature with a slope of 5 mV/K. In some cases, selecting the setpoints is made easier if the TMP12’s internal VPTAT voltage (and therefore the chip temperature) is known. For example, the case temperature of a high power microprocessor can be monitored with a thermistor, thermocouple, or other measurement method. The case temperature can then be correlated with the TMP12’s temperature to select the setpoints.

The TMP12’s VPTAT voltage is not available externally, so indirect methods must be used. Since the VPTAT voltage is applied to the internal comparators, measuring the voltage at which the digital output changes state will reflect the VPTAT voltage.

A simple method of measuring the TMP12 VPTAT is shown in Figure 20. To measure VPTAT, adjust potentiometer R1 until the LED turns ON. The voltage at Pin 2 of the TMP12 will then match the TMP12’s internal VPTAT.

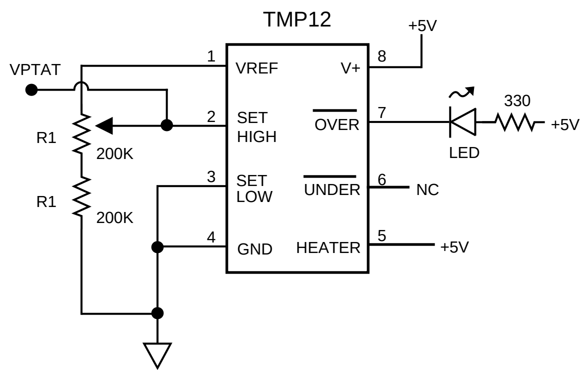


Figure 20. Measuring VPTAT with a Potentiometer

The method described in Figure 20 can be automated by replacing the discrete resistors with a digital potentiometer. The improved circuit, shown in Figure 21, permits the VPTAT voltage to be monitored with a microprocessor or other digital controller. The AD8402-100 provides two 100 kΩ potentiometers which are adjusted to 8-bit resolution via a 3-wire serial interface. The controller simply sweeps the wiper of potentiometer 1 from the A1 terminal to the B1 terminal (digital value = 0), while monitoring the comparator output at Pin 7 of the TMP12. When Pin 7 goes low, the voltage at Pin 2 equals the VPTAT voltage. This Circuit sweeps Pin 2's voltage from maximum to minimum, so that the TMP12's setpoint hysteresis will not affect the reading.

The circuit of Figure 21 provides approximately 1°C of resolution. The two potentiometers divide VREF by two, and the 8-bit potentiometer further divides VREF by 256, so the resolution is:

$$Resolution = \frac{\frac{VREF}{2}}{2N} = \frac{\frac{2.5\ V}{2}}{28} = 4.9\ mV$$

where VREF is the voltage reference output (Pin 1 of the TMP12) and N is the resolution of the AD8402. Since the VPTAT has a slope of 5 mV/K, the AD8402 provides 1°C of resolution. The adjustment range of this circuit extends from VREF/2 (i.e. 1.25 V, or −23°C) to VREF − 1 LSB (i.e. 2.5 V − 4.9 mV, or 226°C). The VPTAT is therefore:

$$VPTAT = 1.25\ V + (Digital\ Count \times 4.9\ mV)$$

where Digital Count is the value sent to the AD8402 which caused the setpoint 1 output to go LOW.

A third way to measure the VPTAT voltage is to close a feedback loop around one of the TMP12’s comparators. This causes the comparator to oscillate, and in turn forces the voltage at the comparator input to equal the VPTAT voltage. Figure 22 is a typical circuit for this measurement. An OP193 operational amplifier, operating as an integrator, provides additional loop-gain to ensure that the TMP12 comparator will oscillate.

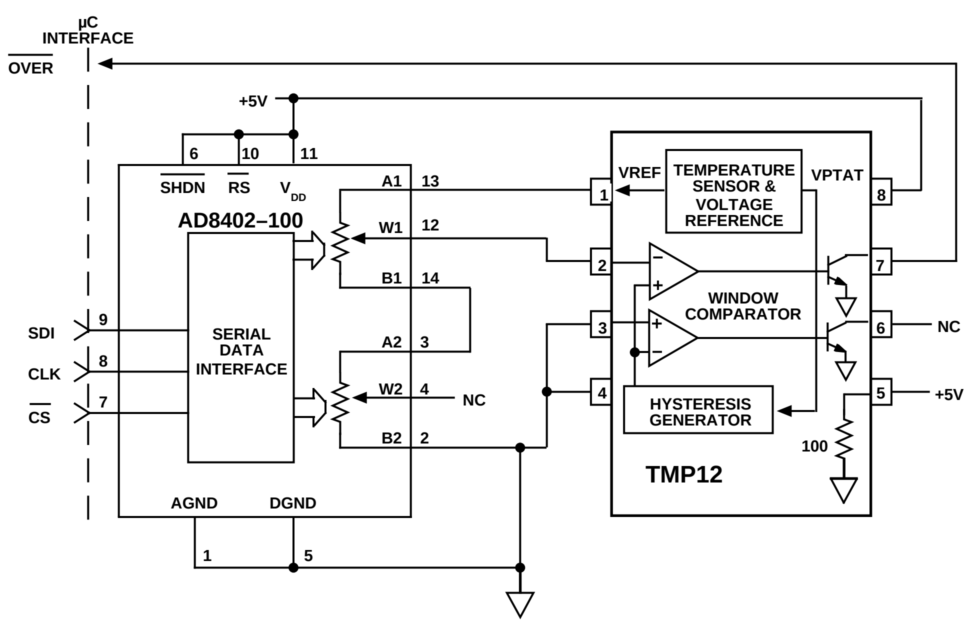


Figure 21. Measuring VPTAT with a Digital Potentiometer

Understanding Error Sources

The accuracy of the VPTAT sensor output is well characterized and specified, however preserving this accuracy in a thermal monitoring control system requires some attention to minimizing the various potential error sources. The internal sources of setpoint programming error include the initial tolerances and temperature drifts of the reference voltage VREF, the setpoint comparator input offset voltage and bias current, and the hysteresis current scale factor. When evaluating setpoint programming errors, remember that any VREF error contribution at the comparator inputs is reduced by the resistor divider ratios. Each comparator's input bias current drops to less than 1 nA (typ) when the comparator is tripped. This change accounts for some setpoint voltage error, equal to the change in bias current multiplied by the effective setpoint divider ladder resistance to ground.

The thermal mass of the TMP12 package and the degree of thermal coupling to the surrounding circuitry are the largest factors in determining the rate of thermal settling, which ultimately determines the rate at which the desired temperature measurement accuracy may be reached (see graph in Figure 3). Thus, one must allow sufficient time for the device to reach the final temperature. The typical thermal time constant for the SOIC plastic package is approximately 70 seconds in still air. Therefore, to reach the final temperature accuracy within 1%, for a temperature change of 60 degrees, a settling time of 5 time constants, or 6 minutes, is necessary. Refer to Figure 4.

External error sources to consider are the accuracy of the external programming resistors, grounding error voltages, and thermal gradients. The accuracy of the external programming resistors directly impacts the resulting setpoint accuracy. Thus, in fixed-temperature applications the user should select resistor tolerances appropriate to the desired programming accuracy. Since setpoint resistors are typically located in the same air flow as the TMP12, resistor temperature drift must be taken into account also. This effect can be minimized by selecting good quality components, and by keeping all components in close thermal proximity. Careful circuit board layout and component placement are necessary to minimize common thermal error sources. Also, the user should take care to keep the bottom of the setpoint programming divider ladder as close to GND (Pin 4) as possible to minimize errors due to IR voltage drops and coupling of external noise sources. In any case, a 0.1 μF capacitor for power supply bypassing is always recommended at the chip.

Safety Considerations in Heating and Cooling System Design

Designers should anticipate potential system fault conditions that may result in significant safety hazards which are outside the control of and cannot be corrected by the TMP12-based circuit. Governmental and Industrial regulations regarding safety requirements and standards for such designs should be observed where applicable.

Self-Heating Effects

In some applications the user should consider the effects of self-heating due to the power dissipated by the open-collector outputs, which are capable of sinking 20 mA continuously. Under full load, the TMP12 open-collector output device is dissipating:

$$P_{DISS} = 0.6\ V \times 0.020\ A = 12\ mW$$

which in a surface-mount SO package accounts for a temperature increase due to self-heating of:

$$\Delta T = P_{DISS} \times \Theta_{JA} = 0.012\ W \times 158°C/W = 1.9°C$$

This increase is for still air, of course, and will be reduced at high airflow levels. However, the user should still be aware that self-heating effects can directly affect the accuracy of the TMP12. For setpoint 2, self-heating will add to the setpoint temperature (that is, in the above example the TMP12 will switch the setpoint 2 output off 1.9 degrees early). Self-heating will not affect the temperature at which setpoint 1 turns on, but will add to the hysteresis. Several circuits for adding external driver transistors and other buffers are presented in following sections of this data sheet. These buffers will reduce self-heating and improve accuracy.

Buffering the Voltage Reference

The reference output VREF is used to generate the temperature setpoint programming voltages for the TMP12. Since the hysteresis is set by the reference current, external circuits which draw current from the reference will increase the hysteresis value.

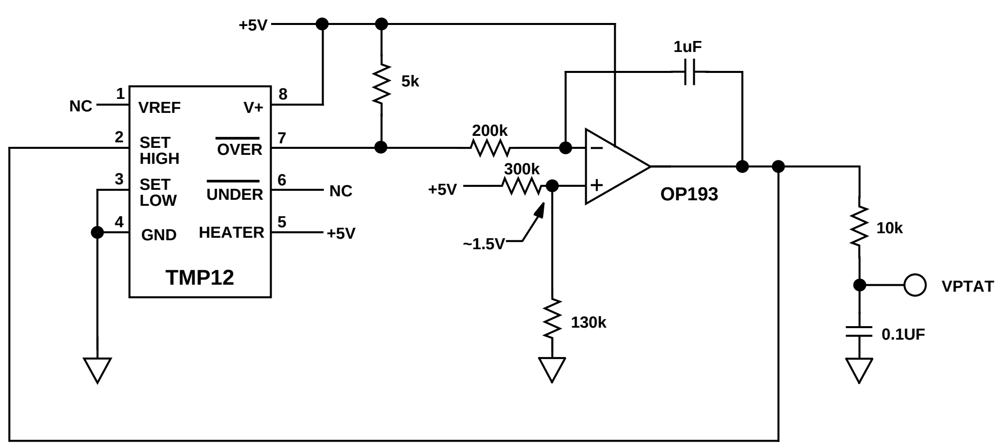


Figure 22. An Analog Measurement Circuit for VPTAT

The on-board VREF output buffer is typically capable of 500 µA output drive into as much as 50 pF load (max). Exceeding this load will affect the accuracy of the reference voltage, could cause thermal sensing errors due to excess heat build-up, and may induce oscillations. External buffering of VREF with a low-drift voltage follower will ensure optimal reference accuracy. Amplifiers which offer low drift, low power consumption, and low cost appropriate to this application include the OP284, and members of the OP113 and OP193 families.

With excellent drift and noise characteristics, VREF offers a good voltage reference for data acquisition and transducer excitation applications as well. Output drift is typically better than −10 ppm/°C, with 315 nV/Hz (typ) noise spectral density at 1 kHz.

Preserving Accuracy Over Wide Temperature Range Operation
The TMP12 is unique in offering both a wide-range temperature sensor and the associated detection circuitry needed to implement a complete thermostatic control function in one monolithic device. The voltage reference, setpoint comparators, and output buffer amplifiers have been carefully compensated to maintain accuracy over the specified temperature ranges in this application. Since the TMP12 is both sensor and control circuit, in many applications the external components used to program and interface the device are subjected to the same temperature extremes. Thus, it is necessary to place components in close thermal proximity minimizing large temperate differentials, and to account for thermal drift errors where appropriate, such as resistor matching temperature coefficients, amplifier error drift, and the like. Circuit design with the TMP12 requires a slightly different perspective regarding the thermal behavior of electronic components.

PC Board Layout Considerations
The TMP12 also requires a different perspective on PC board layout. In many applications, wide traces and generous ground planes are used to extract heat from components. The TMP12 is slightly different, in that ideal path for heat is via the cooling system air flow. Thus, heat paths through the PC traces should be minimized. This constraint implies that minimum pad sizes and trace widths should be specified in order to reduce heat conduction. At the same time, analog performance should not be compromised. In particular, the bottom of the setpoint resistor ladder should be located as close to GND as possible, as discussed in the Understanding Error Sources section of this data sheet.

Thermal Response Time
The time required for a temperature sensor to settle to a specified accuracy is a function of the thermal mass of the sensor, and the thermal conductivity between the sensor and the object being sensed. Thermal mass is often considered equivalent to capacitance. Thermal conductivity is commonly specified using the symbol Q, and is the inverse of thermal resistance. It is commonly specified in units of degrees per watt of power transferred across the thermal joint. Figures 3 and 5 illustrate the typical RC time constant response to a step change in ambient temperature. Thus, the time required for the TMP12 to settle to the desired accuracy is dependent on the package selected, the thermal contact established in the particular application, and the equivalent thermal conductivity of the heat source. For most applications, the settling-time is probably best determined empirically.

Switching Loads with the Open-Collector Outputs
In many temperature sensing and control applications some type of switching is required. Whether it be to turn on a heater when the temperature goes below a minimum value or to turn off a motor that is overheating, the open-collector outputs can be used. For the majority of applications, the switches used need to handle large currents on the order of 1 Amp and above. Because the TMP12 is accurately measuring temperature, the open-collector outputs should handle less than 20 mA of current to minimize self-heating. Clearly, the trip point outputs should not drive the equipment directly. Instead, an external switching device is required to handle the large currents. Some examples of these are relays, power MOSFETs, thyristors, IGBTs, and Darlington transistors.

This section shows a variety of circuits where the TMP12 controls a switch. The main consideration in these circuits, such as the relay in Figure 23, is the current required to activate the switch.

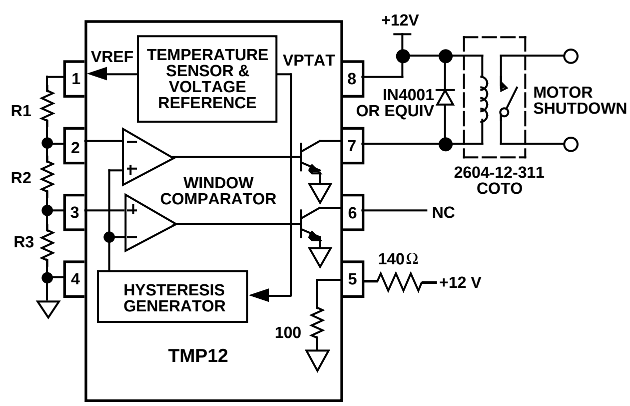


Figure 23. Reed Relay Drive

It is important to check the particular relay you choose to ensure that the current needed to activate the coil does not exceed the TMP12's recommended output current of 20 mA. This is easily determined by dividing the relay coil voltage by the specified coil resistance. Keep in mind that the inductance of the relay will create large voltage spikes that can damage the TMP12 output unless protected by a commutation diode across the coil, as shown. The relay shown has contact rating of 10 Watts maximum. If a relay capable of handling more power is desired, the larger contacts will probably require a commensurably larger coil, with lower coil resistance and thus higher trigger current. As the contact power handling capability increases, so does the current needed for the coil, In some cases an external driving transistor should be used to remove the current load on the TMP12 as explained in the next section.

Power FETs are popular for handling a variety of high current dc loads. Figure 24 shows the TMP12 driving a P-channel MOSFET transistor for a simple heater circuit. When the output transistor turns on, the gate of the MOSFET is pulled down to approximately 0.6 V, turning it on. For most MOSFETs a gate-to-source voltage or Vgs on the order of -2 V to -5 V is sufficient to turn the device on. Figure 25 shows a similar circuit for turning on an N-channel MOSFET, except that now the gate to source voltage is positive. For this reason an external transistor must be used as an inverter so that the MOSFET will turn on when the trip point pulls down.

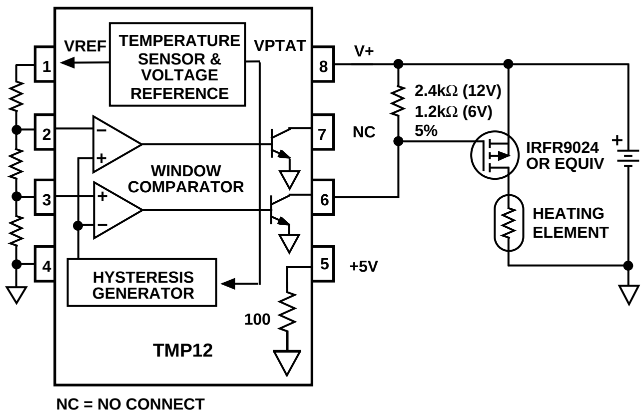


Figure 24. Driving a P-Channel MOSFET

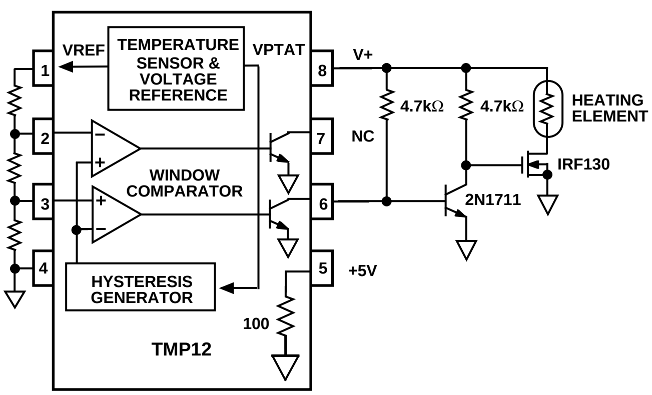


Figure 25. Driving an N-Channel MOSFET

Isolated Gate Bipolar Transistors (IGBTs) combine many of the benefits of power MOSFETs with bipolar transistors and are used for a variety of high power applications. Because IGBTs have a gate similar to MOSFETs, turning on and off the devices is relatively simple as shown in Figure 26. The turn on voltage for the IGBT shown (IRGB40S) is between 3.0 and 5.5 volts. This part has a continuous collector current rating of 50 A and a maximum collector to emitter voltage of 600 V, enabling it to work in very demanding applications.

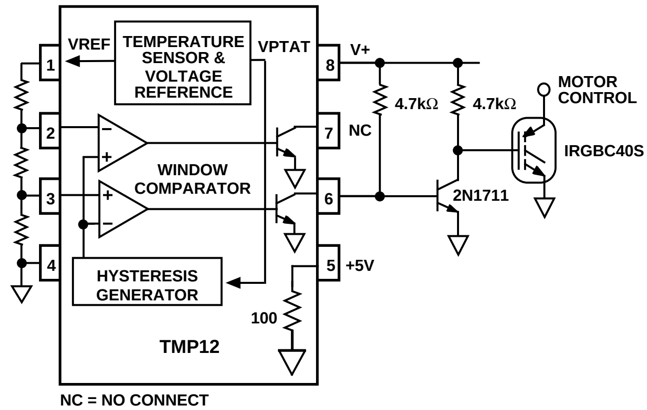


Figure 26. Driving an IGBT

The last class of high power devices discussed here are Thyristors, which include SCRs and Triacs. Triacs are a useful alternative to relays for switching ac line voltages. The 2N6073A shown in Figure 27 is rated to handle 4 A (rms). The opto-isolated MOC3021 Triac shown features excellent electrical isolation from the noisy ac line and complete control over the high power Triac with only a few additional components.

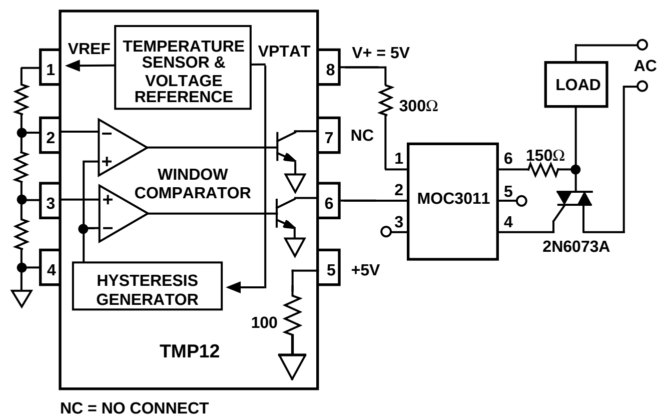


Figure 27. Controlling the 2N6073A Triac

High Current Switching

As mentioned earlier, internal dissipation due to large loads on the TMP12 outputs will cause some temperature error due to self-heating. External transistors buffer the load from the TMP12 so that virtually no power is dissipated in the internal transistors and minimal self-heating occurs. This section shows several examples using external transistors. The simplest case uses a single transistor on the output to invert the output signal is shown in Figure 28. When the open-collector of the TMP12 turns “ON” and pulls the output down, the external transistor Q1’s base will be pulled low, turning off the transistor. Another transistor can be added to re-invert the signal as shown in Figure 29. Now, when the output of the TMP12 is pulled down, the first transistor, Q1, turns off and its collector goes high, which turns Q2 on, pulling its collector low. Thus, the output taken from the collector of Q2 is identical to the output of the TMP12. By picking a transistor that can accommodate large amounts of current, many high power devices can be switched.

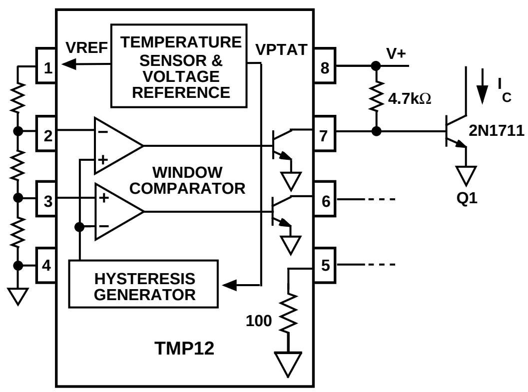


Figure 28. An External Transistor Minimizes Self-Heating

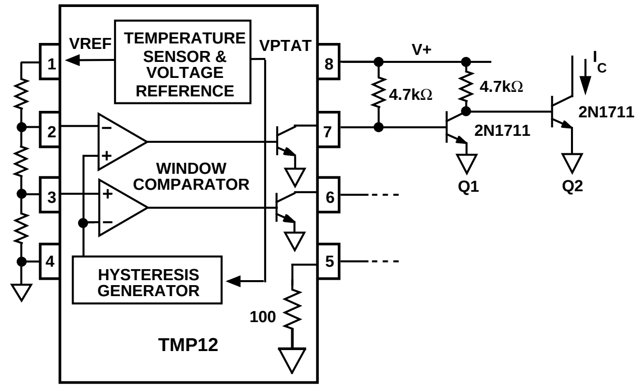


Figure 29. Second Transistor Maintains Polarity of TMP12 Output

An example of a higher power transistor is a standard Darlington configuration as shown in Figure 30. The part chosen, TIP-110, can handle 2 A continuous which is more than enough to control many high power relays. In fact the Darlington itself can be used as the switch, similar to MOSFETs and IGBTs.

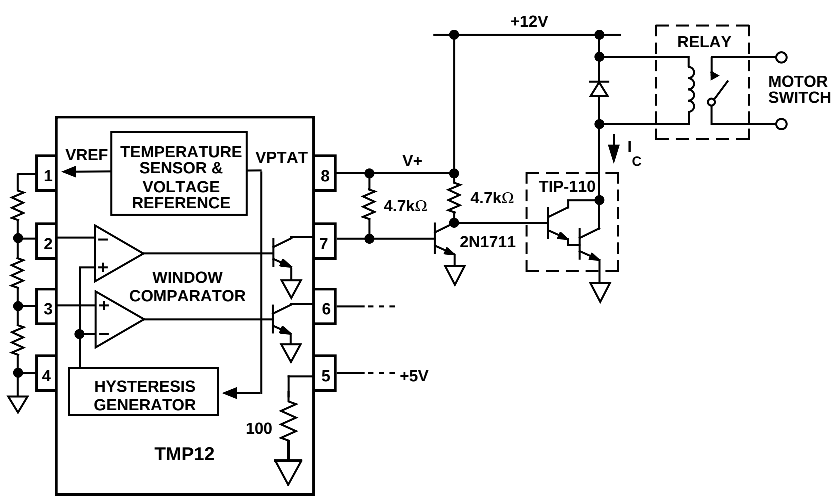
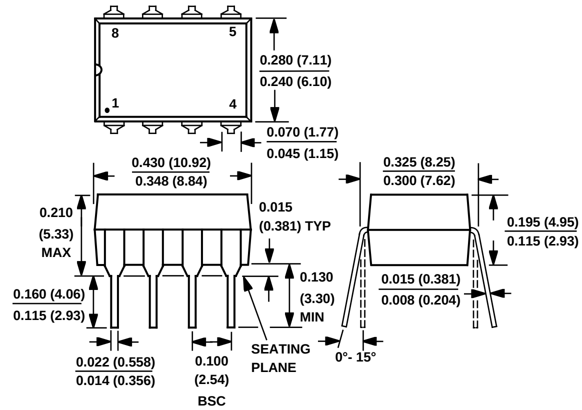


Figure 30. Darlington Transistor Can Handle Large Currents

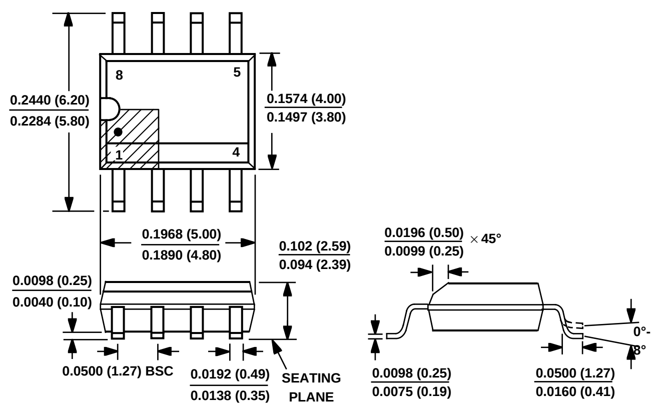
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

8-Pin Epoxy DIP



8-Pin SOIC



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