Mechatronics & Embedded Microcomputer Control
ME E4058 Spring 2017

Case Study #4: On / Off Temperature Control

This case study is a dynamic system investigation of an important and common mechatronic system: a thermal closed-loop control system. Temperature regulation is a common control problem. Temperature control systems are found in a variety of commercial products. In our homes, we find temperature regulation devices that maintain the temperature of our rooms and regulate the temperature of our ovens, toasters, coffee pots and refrigerators. In our cars, we find temperature control mechanisms that regulate the temperature of our engine to preserve the integrity of the lubrication and combustion processes. Office equipment, such as xerographic and facsimile machines, have sophisticated control mechanisms that regulate the temperatures of the fuser (which thermally fuses the image to paper) and thermal transfer rolls. Many industrial processes include temperature control subsystems. Catalytic chemical processes, for example, regulate the rate of the chemical reaction by controlling the temperature of the reactor with reactant flow heat exchangers and control valves. This case study explores methods of controlling the production of heat energy for the purpose of producing a desired temperature in a device. As with the other case studies, the device that you will investigate is simple but the techniques that you will learn are applicable to a wide variety of industrial temperature control systems.

The apparatus that will be investigated includes a resistive heater, two temperature sensors, and a fan. The objective of the case study is to control the temperature of a thin aluminum plate, as measured by a temperature sensor positioned in the middle of the top of the plate, by regulating the power supplied to a resistive heater positioned under the plate. There is an a.c. (alternating current) fan positioned above the plate which will cool the plate when activated by changing the heat transfer from free to forced convection. The temperature is to be regulated to a point 50° C above the temperature of the ambient air which is measured with the other temperature sensor. The measured voltage from the two temperature sensors will be input to the embedded microcontroller via the on-chip A/D converter (i.e. they will be measured as analog quantities to the resolution of the A/D converter). The ambient temperature sensor will provide the setpoint to the temperature control system. The plate temperature sensor provides the feedback signal.

The general steps in the case study will involve:

- understanding the physical system, , understanding the sensors and actuator, understanding the control issues

- designing an on/off feedback control system to meet the performance specifications

- implementing the control system and experimentally demonstrating its predicted performance

The goal in the fourth case study is to provide an understanding of the issues and techniques for temperature control using an embedded microcontroller.

Introduction:

The physical system that we are investigating is illustrated in Figure 1. The goal is to control the temperature of an aluminum plate, two inches square and 0.06 inch thick. This thin plate is heated on its underside by a thin-film flexible resistive heater, which converts electrical energy to thermal energy through, essentially, the losses in a resistor. The heat supplied by the heater to the plate depends on the power dissipation in the heater, which is a function of both the current applied to the heater and the heater's resistance. The resistive heater is insulated on its underside by a wood block to inhibit the conductive transfer of heat from the bottom of the resistive heater to the stand. The stand is fabricated of Plexiglas which is also thermally insulating in nature. The thermal conductivity *k* of the wood block insulation is 0.14 W/m-K compared to 177 W/m-K for the aluminum plate. The top of the thin, heated, aluminum plate is exposed to ambient air. Contacting the heated plate is a temperature sensor whose electrical properties vary with the temperature of the surface it contacts. A second temperature sensor is attached to the top of the fixture to measure the temperature of the ambient air. Above the plate in the fixture is mounted an a. c. motor fan which can be used to cool the plate from above by the convective heat transfer of the moving air.

It should be realized that the plate loses heat to convection even if the fan is off. With the fan off, losses from the plate are due to free convection off the flat plate surface. With the fan on, losses from the plate are due to the forced convection of the fan.

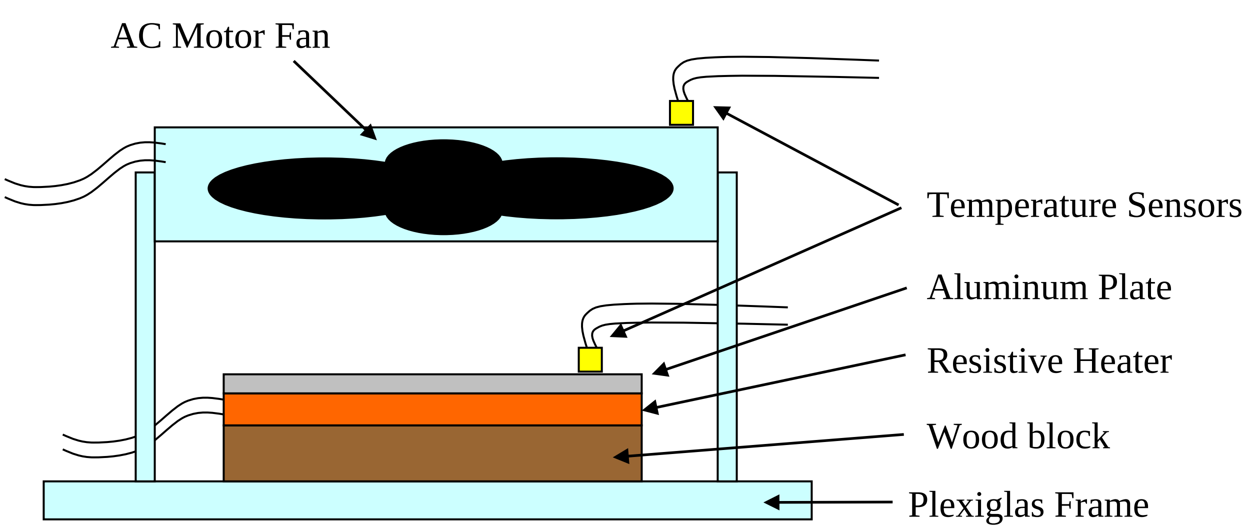

Figure 1. Schematic of Temperature Control Test Stand

A picture of the test stand is shown in Figure 2.

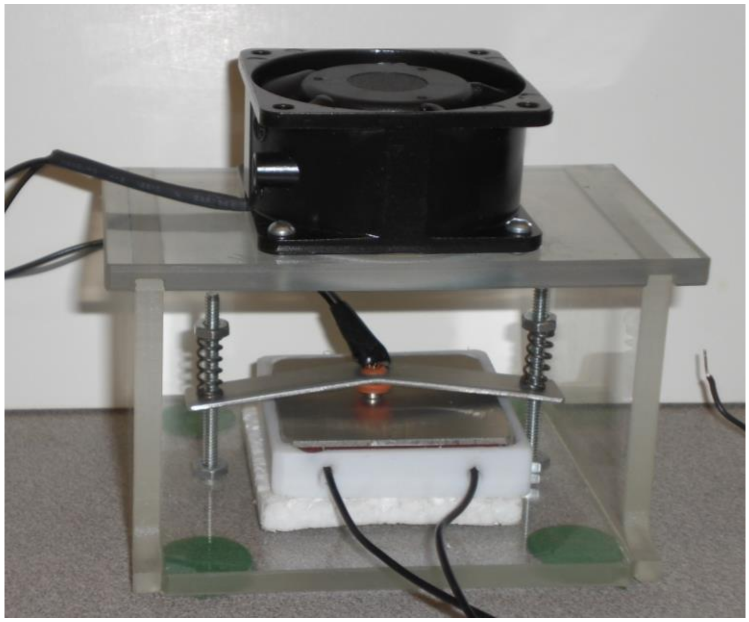

Figure 2. Photo of Temperature Control Test Stand

The commercial resistive heater is supplied by Omega Engineering Inc. Its specifications are listed in Table 1.

Specifications	Value
Manufacturer	Omega Engineering Inc
Model Number	SRMU100202P
Heater Resistance	350 ohms
Heater Area	4 in^2
Heater Thickness	0.1 in

Table 1. Properties of the Resistive Heater

The temperature sensors are manufactured by Analog Devices. The specifications for the devices are listed in Table 2. The essential difference is that one device (AD590) used for the temperature of the plate, produces a current proportional to temperature while the second (AD22100), used to measure ambient, produces a voltage proportional to temperature. From

Figure 3, which is a block diagram of the AD22100 part, it can be seen that it contains a resistor proportional to temperature which converts a current to a voltage. Also, the temperature coefficient for the sensor is a function of the supply voltage for the device. For higher accuracy, we will be using a precision voltage reference both for the sensor supply voltage and the reference for the microcomputer A/D converter. The voltage reference produces a voltage of 4.096 V from a 5 V supply. The temperature coefficient of the AD22100 is the following:

$$V_{ambient} = \frac{V_{ref}}{5.0\,V}\ 22.5\ \frac{mV}{{}^{0}C} = 18.43\ \frac{mV}{{}^{0}C}$$

If you include the nominal output voltage at 0^0 C, the equation for the sensor becomes:

$$V_{ambient} = \left(18.43\ \frac{mV}{{}^{0}C}\right)\left(\text{Temperature}\ ({}^{0}C)\right) + 1.126\,V$$

Specification	AD590	AD22100
Rated Temperature Range	-55° C to 150° C	0° C to 100° C
Nominal Output at 0° C	273.2 µA	1.126 V
Nominal Output at 25° C	298.2 µA	1.587 V
Temperature Coefficient	1 µA / ° C	18.43 mV / ° C
Absolute Error	± 5.5° C	± 2.0° C
Nonlinearity	0.8° C	0.5° C

Table 2. Properties of the Temperature Sensors

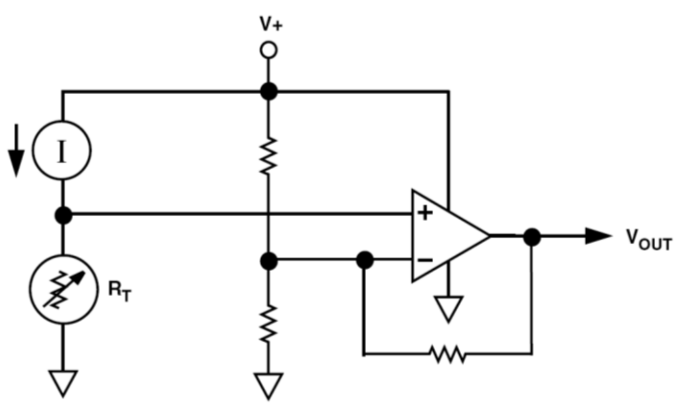

Figure 3. Simplified Schematic of the AD22100 Temperature Sensor.

For this case study, we will be using the AD22100 sensor for ambient temperature since it offers easier interfacing to the A/D converter on the microcomputer. Its physical package does not make it easy to contact the aluminum plate so the AD590 sensor is used for this purpose.

You can use any 2 of the analog multiplexor terminals of the microcomputer for the temperature inputs and but you must use pin 3 of Port A for the voltage reference. (Why?) The circuit shown in Figure 4 is the interface for the ambient temperature sensor A/D input. Note the passive filter and the OpAmp used as a buffer. From your work with the Analog Case Study, you should understand how this circuit works.

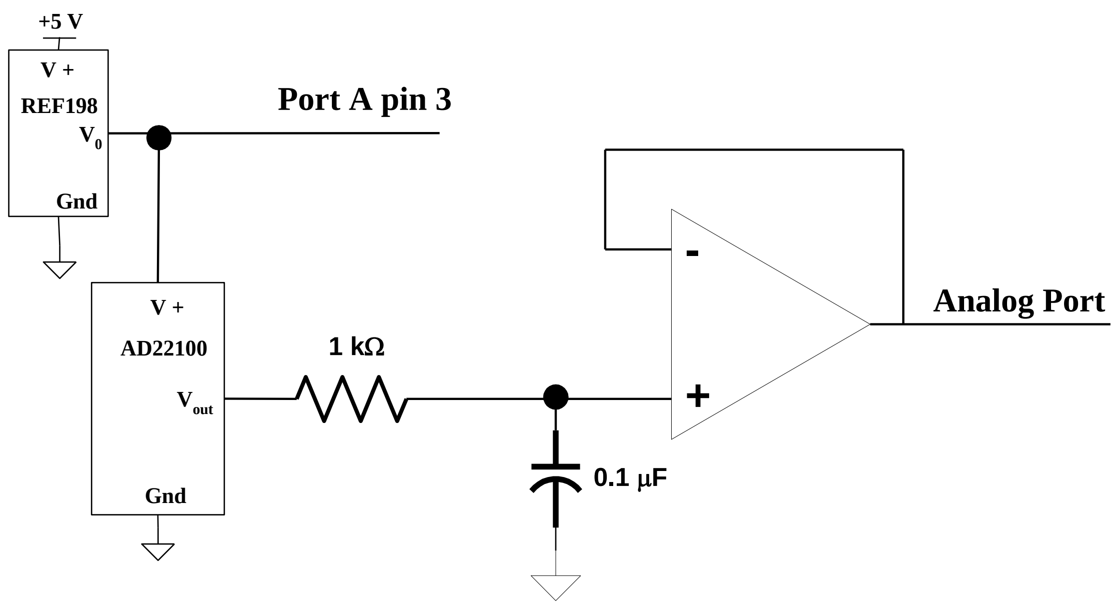

Figure 4. Interface Circuit for the Ambient Temperature Sensor

The temperature feedback sensor (contacting the aluminum plate) is an AD590 sensor. As can be seen from the circuit in Figure 5, the temperature sensor (with a 5 volt voltage source) acts like a current source of 1 μA / ^{0}K and is connected in series with a 1 kΩ resistor. The voltage across the resistor with respect to ground is connected to an OpAmp. From your work with the Analog Case Study, you should also understand how this circuit works. The gain of this sensor after amplification in Volts / ^{0}K is:

$$V_{feedback} = \left(34.75 \ \frac{\text{mV}}{{}^{0}\text{K}} \right) \left(\text{Temperature } ({}^{0}\text{K}) \right) - 10.29 \text{ V}$$

The single supply rail-to-rail OpAmp in the figure performs three functions:

1. It scales the temperature signal to span the range of the A/D converter.
2. It offsets the temperature signal to eliminate the voltage due to ambient temperature.
3. It filters the temperature reading to avoid aliasing in the A/D converter. Because the aluminum plate has substantial thermal capacitance, any high frequency voltage from the sensor will be due to electrical noise. This signal should be filtered so that it does not appear to be a low frequency temperature fluctuation resulting from aliasing with the sampling frequency.

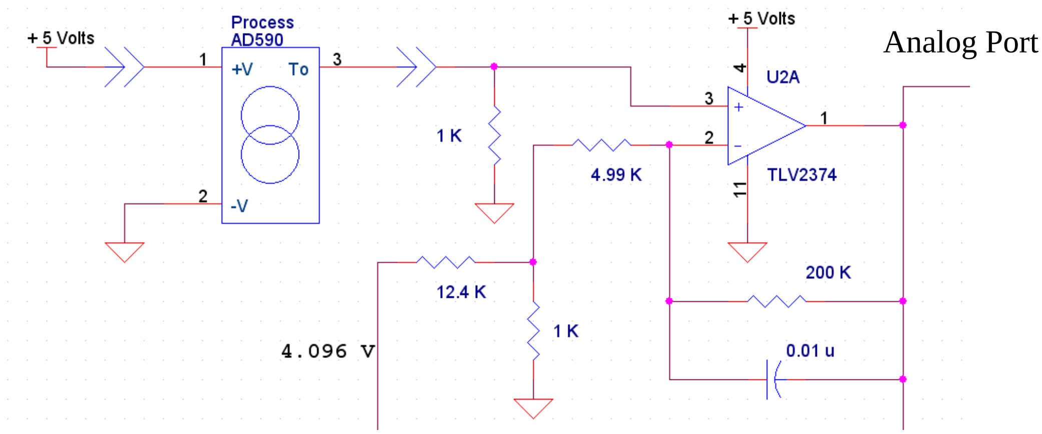

Figure 5. Interface Circuit for the Feedback Temperature Sensor

When analyzing single supply rail-to-rail OpAmps, you should realize that the output signal is cannot go below 0 V since this is the lower voltage rail (pin 11). Thus useful bipolar signals are centered around ½ the supply voltage (i.e. 2.5 V with the 5V supply). Thus when V+ is less than V-, the output will be 0 V. The OpAmp will also draw large currents if either voltage goes negative by more than 0.3 V. Often when using these OpAmps, one or both voltages are biased around 2.5 V. If you are aware of these restrictions, all the standard OpAmp analyses apply. With the resistor divider providing the offset voltage at V-, the output voltage will be zero with the plate temperature of about 25 ^{0}C (room temperature). Since this circuit is a differential amplifier, the equation that relates V_o to V_i (the input voltage from the sensor) and V_r (the reference voltage at the voltage divider) is:

$$V_o = -\frac{Z_f}{R_i} V_r + \frac{Z_f}{R_i} V_i + V_i$$

In this equation, Z_f is the parallel impedance of the feedback resistor and capacitor. The resistance R_i includes the resistor connected to the negative input terminal and the parallel combination of the voltage divider resistors.

The plate is made of 6061 aluminum. The relevant physical properties of aluminum are listed in Table 3.

Property	Value
Melting Point	775^0 K
Density, ρ	2770 kg/m^3
Specific Heat, σ	875 J / (kg - ^{0}K)
Thermal Conductivity, k	177 W / (m - ^{0}K)

Table 3. Material Properties of 6061 Aluminum

Background Information

Physical Model

To design a control system for this thermal system, we should first analyze the thermal system. The first step in the analysis is the development of a model for the system. While not required for this case study, the essential steps in formulating a model are discussed. The challenges in the physical modeling this system are formidable in spite of its seeming simplicity:

- The dynamic behavior of many of the physical processes involved is complex.
- The cause and effect relationships are not easily discernible.
- Many important variables are not readily identified.
- Interactions among the variables are hard to capture.

The first step in physical modeling is to specify the system to be studied, its boundaries, and its inputs and outputs. One then imagines a simple physical model whose behavior will match sufficiently closely the behavior of the actual system. A physical model is an imaginary physical system which resembles the actual system in its salient features but which is simpler (more "ideal") and is thereby more amenable to analytical studies. It is not oversimplified, not overly complicated - it is a slice of reality. The astuteness with which approximations are made at the outset of an investigation is the very crux of engineering analysis. The ability to make shrewd and viable approximations which greatly simplify the system and still lead to a rapid, reasonably accurate prediction of its behavior is the hallmark of every successful engineer. This ability involves a special form of carefully developed intuition known as *engineering judgment*. An additional consideration that determines the structure of a model is how the model will be used. If we want to model the thermal system so that we can use the model to design a control system, the model should capture the system dynamics and be amenable to control system analysis. We should also have a good degree of confidence that the controller designed for the model will perform adequately on the real system.

Table 4 lists some of the approximations used in the physical modeling of dynamic systems and the mathematical simplifications that result. These assumptions lead to a physical model whose mathematical model consists of linear, ordinary differential equations with constant coefficients. This type of mathematical model can be analyzed with a variety of tools and produce results that have been verified in a large number of cases.

Approximation	Mathematical Simplification
Neglect small effects	Reduces the number and complexity of the equations of motion
Assume the environment is independent of system operation	Reduces the number and complexity of the equations of motion
Replace distributed characteristics with appropriate lumped elements	Leads to ordinary (rather than partial) differential equations
Assume linear relationships	Makes equations linear; allows superposition of solutions
Assume constant parameters	Leads to constant coefficients in the differential equations
Neglect uncertainty and noise	Avoids statistical treatment

Table 4. Approximations Used in Physical Modeling.

The following briefly discusses these assumptions.

<u>Neglect Small Effects</u>
Small effects are neglected on a relative basis. In analyzing the motion of an airplane, we are unlikely to consider the effects of solar pressure, the earth's magnetic field, or gravity gradient. To ignore these effects in a space vehicle problem would lead to grossly incorrect results.

<u>Independent Environment</u>
Here we assume that the environment, of which the system under study is a part, is unaffected by the behavior of the system, i.e., there are no loading effects. In analyzing the vibration of an instrument panel in a vehicle, for example, we assume that the vehicle motion is independent of the motion of the instrument panel. If loading effects are possible, then either steps must be taken

to eliminate them (e.g., use of buffer amplifiers discussed in the analog case study), or they must be included in the analysis. For the thermal case study, it seems unlikely that the heat produced by the 4 in^2 heater will increase the temperature of the room significantly.

Lumped Characteristics

In a lumped-parameter model, system dependent variables are assumed uniform over finite regions of space rather than over infinitesimal elements, as in a distributed-parameter model. Time is the only independent variable and the mathematical model is an ordinary differential equation. In a distributed-parameter model, time and spatial variables are independent variables and the mathematical model is a partial differential equation in the time and spatial variables. Note that elements in a lumped-parameter model do not necessarily correspond to separate physical parts of the actual system. A long electrical transmission line has resistance, inductance, and capacitance distributed continuously along its length. These distributed properties are often approximated by lumped elements at discrete points along the line.

Linear Relationships

Nearly all physical elements or systems are inherently nonlinear if there are no restrictions at all placed on the allowable values of the inputs. If the excursion of the inputs are confined to a sufficiently small range, the original nonlinear model of the system may often be replaced by a linear model whose response closely approximates that of the nonlinear model. When a linear differential equation has been solved once, the solution is general, holding for all magnitudes of input and output. Linear systems also satisfy the properties of superposition and homogeneity. The superposition property states that for a system initially at rest with zero energy, the response to several inputs applied simultaneously is the sum of the individual responses to each input applied separately. The homogeneity property states that multiplying the input to a system by any constant multiplies the output by the same constant. There are also a multitude of analytical tools available for linear system models so linear models are always preferable even if the excursion range is small.

Constant Parameters

Time-varying systems are ones whose characteristics change with time. Physical problems are simplified by the adoption of a model in which all the physical parameters are constant.

Neglect Uncertainty and Noise

In real systems we are uncertain, to varying degrees, about values of parameters, about measurements, and about expected inputs and disturbances. Disturbances contain random inputs, which can influence system behavior. Sensors and actuators contain noise, which can appear to be disturbances to the system behavior. It is common in analysis to neglect such uncertainties and noise and proceed as if all quantities have definite values that are known precisely.

Thermal System Simplifying Assumptions:

1. The temperature of the plate is uniform.

2. There in no heat loss through the sides of the plate, i.e., heat conduction is one-dimensional from the heater through a thermal contact resistance and through the plate from bottom to top.

3. The thermal conductivity of the plate is constant, i.e., independent of time, temperature, space, or direction of heat flow.

4. The heat loss due to radiation is negligible compared to the convective heat loss from the plate. (This of course can be verified if the temperature of the surrounding medium (the inside of the test fixture) were measured.

5. The heat convection coefficient is constant and is evaluated at the operating temperature of the plate.

6. The heat loss through the insulating (Wood block) layer is negligible, i.e., heat loss through the insulating layer, and subsequent convective heat loss from the bottom supporting plexiglass plate, is negligible compared to the other heat losses in the system.

7. The sensor dynamics are negligible, i.e., the sensor dynamics are very fast relative to the dynamics of the rest of the system. This includes the dynamics of the OpAmp interface circuit.

8. Ambient air temperature is unaffected by the heat flux from the plate.

These assumptions lead to the simplifications shown in the diagram of Figure 6. This is the resulting physical model.

Mathematical Model

The steps in mathematical modeling the system are as follows:

- Define system, system boundary, system inputs and outputs
- Define through and across variables
- Write physical relations for each element using the element law
- Write system relations of equilibrium and/or compatibility
- Combine system relations and physical relations to generate the mathematical model for the system

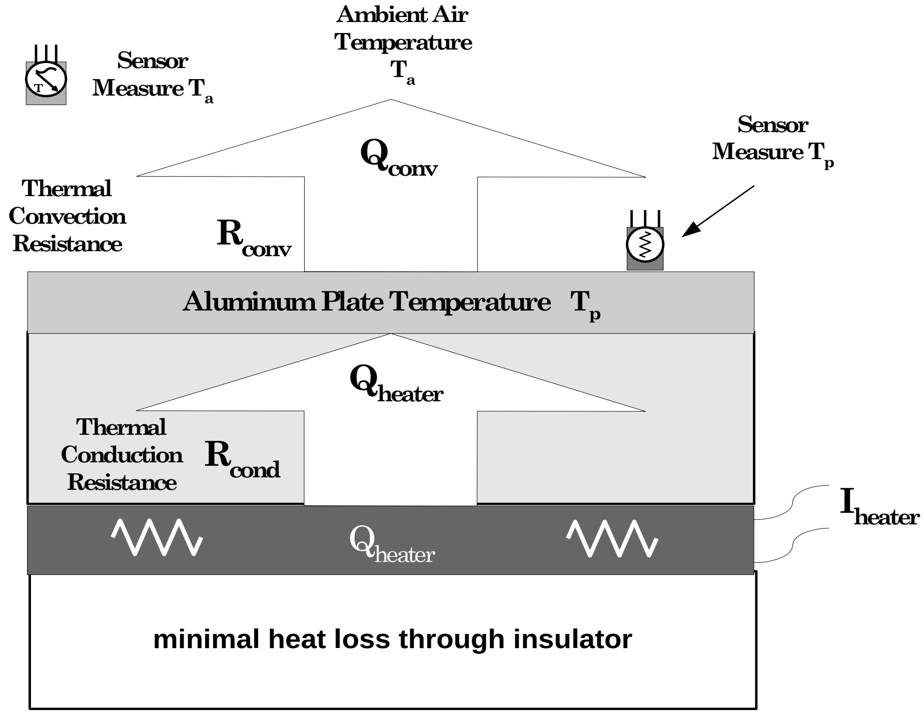

Figure 5. Diagram of the Physical Model.

We will look at each step more closely and then apply these steps to our physical model.

- *Define system, system boundary, system inputs and outputs*: A system must be defined before equilibrium and/or compatibility relations can be written. Unless physical boundaries of a system are clearly specified, any equilibrium and/or compatibility relations we may write are meaningless. System outputs to the environment and system inputs from the environment must be also clearly defined.

- *Define through and across variables*: Precise physical variables (velocity, voltage, pressure, flow rate, etc.) used to describe the state of a system and its behavior must be selected. Recall that physical variables may be classified as:

  - *Through variables* (one-point variables) measure the transmission of something through an element, e.g., electric current through a resistor, fluid flow through a duct, force through a spring, etc.

  - *Across variables* (two-point variables) measure a difference in state between the ends of an element, e.g., voltage drop across a resistor, pressure drop between the ends of a duct, difference in velocity between the ends of a damper, etc.

- *Write physical relations for each element*: Write the natural physical laws which the individual elements of the system obey, e.g., mechanical relations between force and motion, electrical relations between current and voltage, electromechanical relations between force and magnetic field, thermodynamic relations between temperature, pressure, etc. These relations are called constitutive physical relations as they concern only individual elements or constituents of the system. They are relations between the through and across variables of each individual physical element and may be algebraic, differential, integral, linear or nonlinear, constant or time-varying. They are purely empirical relations observed by experiment and not deduced from any basic principles. Examples of these are Hooke's law for a spring or Ohm's law for a resistor. Also write any energy conversion relations, e.g., electrical-electrical (transformer), electrical-mechanical (motor or generator), mechanical-mechanical (gear train). These relations are between across variables and between through variables of a coupled system.

- *Write system relations of equilibrium and/or compatibility*: Dynamic equilibrium relations describe the balance of forces, of flow rates, of energy which must exist for the system and its subsystems. Equilibrium relations are always relations among through variables, e.g., Kirchhoff's Current Law (at an electrical node), continuity of fluid flow, equilibrium of forces meeting at a point. Compatibility relations describe how motions of the system elements are interrelated because of the way they are interconnected. These are inter-element or system relations. Compatibility relations are always relations among across variables, e.g., Kirchhoff's Voltage law around a circuit, pressure drop across all the connected stages of a fluid system, geometric compatibility in a mechanical system.

- *Combine system relations and physical relations to generate the mathematical model for the system*: The mathematical model can be an input-output differential equation, a transfer function, a block diagram or a set of state-variable equations. A state-determined system is a special class of lumped-parameter dynamic systems such that: (i) the specification of a finite set of n independent parameters (the *state variables)* at time $t = t_0$ and (ii) the specification of the system inputs for all time $t \geq t_0$ are necessary and sufficient to uniquely determine the response of the system for all time $t \geq t_0$. The *state* is the minimum amount of information needed about the system at time t_0 such that its future behavior can be determined without reference to any input before t_0.

We will now apply these steps to the thermal system in the case study.

- *Define system, system boundary, system inputs and outputs*:
  Figure 6 shows the physical model of the physical system, identifying the system and the system boundary. The input to the system is the current supplied to the resistive heater $\mathbf{V_{heater}}$ and the output of the system is the plate temperature as measured by the temperature sensor attached to the top of the plate $\mathbf{T_p}$.

- *Define through and across variables:*

The through variable is the heat flow rate $\mathbf{Q_{heater}}$ (J/s or W) and the across variable is the temperature $\mathbf{T_p}$ (^{0}C). We assume that all points in the body (the plate) have the same temperature (average temperature) and temperature deviations from the average at various points do not affect the validity of the single-temperature model. If this is not the case, the body may be partitioned into segments, each of which has an average temperature associated with it. Measurement of these temperatures would be difficult. Since temperature is a measure of the energy stored in a body, we normally select the temperatures as the state variables of a thermal system.

- *Write physical relations for each element:*
  There are only two types of passive thermal elements: thermal capacitance and thermal resistance. We also need to consider thermal sources.

  <u>Thermal Capacitance</u>
  When heat flows into a body of solid, liquid, or gas, this thermal energy may show up in various forms such as mechanical work or changes in kinetic energy of a flowing fluid. If we restrict ourselves to bodies of material for which the addition of thermal energy does not cause significant mechanical work or kinetic energy change, the added energy shows up as stored internal energy and manifests itself as a rise in temperature of the body. A physical body at a uniform temperature will have an algebraic relationship between its temperature and the heat stored in it. Provided that there is no change of phase and that the range of temperatures is not excessive, this relationship can be considered to be linear.

$$Q_{in}(t) - Q_{out}(t) = \text{net heat flow rate into body}$$

$$\int_{t_0}^{t} \left[Q_{in}(\lambda) - Q_{out}(\lambda) \right] d\lambda = \text{net heat supplied between times } t_0 \text{ and } t$$

Assume that heat supplied during this time interval equals a constant **C** times **ΔT**.

$$C\ \Delta T = C\left[T(t) - T(t_0) \right] = \int_{t_0}^{t} \left[Q_{in}(\lambda) - Q_{out}(\lambda) \right] d\lambda$$

where **C** is the thermal capacitance (J / ^{0}C) and is equal to $\boldsymbol{M}\ \boldsymbol{\sigma}$, where $\boldsymbol{M}$ is the mass of the body (kg) and $\boldsymbol{\sigma}$ is the specific heat of the body (J / [kg – ^{0}C]). Differentiating the above equation results in:

$$\dot{T} = \frac{1}{C} \left[Q_{in}(t) - Q_{out}(t) \right]$$

We can use this equation only when the temperature of the body is assumed uniform. If thermal gradients within the body are so great that we cannot make this assumption, then the body should be divided into two or more parts with separate thermal capacitances.

Thermal Resistance

Whenever two objects have different temperatures, there is a tendency for heat to be transferred from the hot region to the cold region in an attempt to equalize temperatures. For a given temperature difference, the rate of heat transfer varies depending on the thermal resistance of the path between the hot and cold region. The nature and magnitude of the thermal resistance depend on the modes of heat transfer involved: conduction, convection, or radiation.

Conduction: In conduction, heat flows from one body to another through the medium connecting them at a rate proportional to the temperature difference between the points:

$$Q(t) = \frac{1}{R}\left[T_1(t) - T_2(t)\right]$$

where **R** is the thermal resistance ([^{0}C – s] / J or ^{0}C / W) which equals *L / Ak*, where *A* is the cross-sectional area of the heat flux path, *L* is the length of the path, and *k* is the thermal conductivity of the material (W / [m –^{0}C]). We can use this equation only when the body is being treated as a thermal resistance and does not store any heat.

Convection: Many practical situations involve heat flow through fluid / solid interfaces by convection. In this case, heat flows by conduction through a thin layer of fluid (called the boundary layer) which adheres to the solid wall. At the interface between the boundary layer and the main body of fluid, the heat is carried away by the constantly moving fluid particles into the main stream. This overall process is called convection and is described by the equation:

$$Q(t) = h\,A\left[T_1(t) - T_2(t)\right]$$

where **h** is the film coefficient of heat transfer (J / [s – m^2 – ^{0}C] or W / [m^2 – ^{0}C]) and **A** is the surface area (m^2). While techniques exist to estimate **h**, in practice the value is often experimentally determined and usually varies with temperature. For the purpose of this case study, we will assume that **h** is a constant.

Radiation: Two bodies can exchange thermal energy with no physical contact by the process of radiation. The rate of heat transfer depends on a surface property of each body called the emissivity ε, geometrical factors involving the portion of the emitted radiation from one body that actually strikes the other body, the surface areas involved, and the temperatures of the two bodies. For a typical configuration and materials, the defining equation takes the form:

$$Q(t) = \varepsilon\,A\left[T_1^4(t) - T_2^4(t)\right] + D$$

where *D* includes all the effects other than the temperatures and is usually quite small. For this equation, the temperatures are absolute.

Thermal Sources: A thermal source can be one that adds or removes heat at a specified rate, or can take the form of a temperature of a body as a known function of time regardless of the rate at which heat flows between the body and the rest of the system. In other words, the thermal source can be either a source of heat flux or temperature and is thus analogous to current and voltage sources in electrical systems. For this thermal system, the resistive heater electrical model is shown schematically in Figure 7, where $\mathbf{R_{heater}}$ is the heater resistance, $\mathbf{I_{heater}}$ is the heater current, and $\mathbf{V_{heater}}$ is the heater voltage.

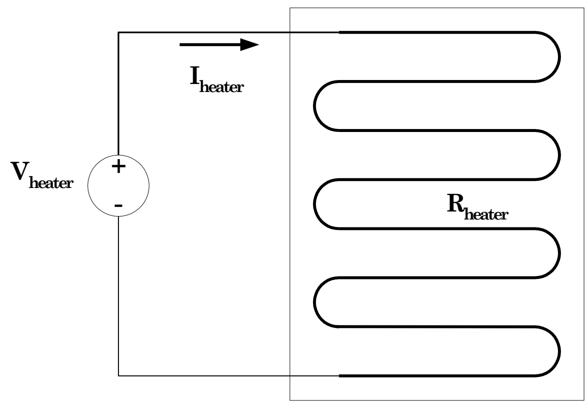

Figure 7. Electrical Model of the Resistive Heater

If we assume 100% conversion efficiency, the heat flux produced by the resistive heater is equivalent to the power dissipated across the resistive element. The power dissipated across the resistive heater P_{heater} (J / s or W) is given by:

$$Q_{heater} = P_{heater} = V_{heater} \ I_{heater} = \frac{V_{heater}^{\ 2}}{R_{heater}}$$

- *Write system relations of equilibrium and/or compatibility:*
  Referring to the physical model of Figure 5, relations have to be written for the thermal capacitance and the convection thermal resistance. Although there is some conduction thermal resistance between the heater and the plate produced by the contact adhesive, since we assume that all the heat produced by the heater enters the plate, the value of this conduction resistance is not needed for our model. (Note that a more typical arrangement is that the heat flux is unknown and the temperature of the interface between the heater and the plate is measured with a sensor to determine the heat flux. In this case, the conduction resistance must be included in the model.) Using the variables from Figure 5, the relations for the thermal capacitance and convection resistance is as follows.

  Thermal Capacitance:

$$\dot{T}_p = \frac{1}{C_p} \left[Q_{heater}(t) - Q_{conv}(t) \right]$$

Note that in a state variable model, the temperature of each thermal capacitance is typically chosen as the state variables since the temperature determines the internal energy in the thermal capacitance. The net heat flow rate into a thermal capacitance depends on the heat sources and heat flow rates through the thermal resistances.

<u>Thermal Resistance</u>:

$$Q_{conv}(t) = \frac{1}{R_{conv}} \left[T_p(t) - T_a(t) \right]$$

where the thermal resistance is

$$R_{conv} = \frac{1}{h_p \; A_p}$$

where $\mathbf{h_p}$ is the film coefficient of heat transfer and $\mathbf{A_p}$ is the surface area of the plate.

- *Combine system relations and physical relations to generate the mathematical model for the system*:
  Problems in heat transfer are often solved by modeling the thermal resistances by electrical resistances, the thermal capacitances by electrical capacitances and the sources by electrical sources. Kirchhoff's Voltage and Current Laws are then used to generate the mathematical heat transfer model. An equivalent electrical circuit for this system is shown in Figure 8.

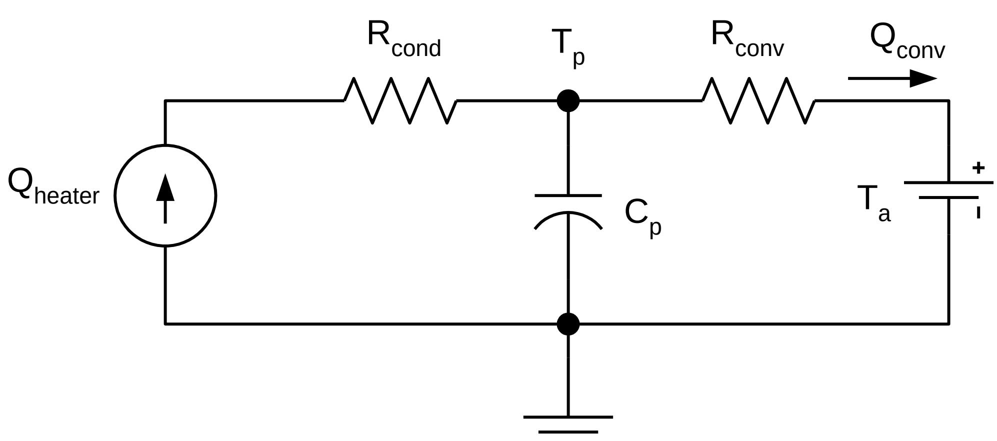

Figure 8. Equivalent Circuit for the Thermal System

The defining equations are:

$$Q_{heater} = I_{heater}^{2} R_{heater}$$

$$Q_{conv}(t) = \frac{1}{R_{conv}} \left[T_p(t) - T_a(t) \right]$$

$$\dot{T}_p = \frac{1}{C_p} \left[Q_{heater}(t) - Q_{conv}(t) \right] = \frac{1}{C_p} \left[Q_{heater}(t) - \frac{1}{R_{conv}} \left[T_p(t) - T_a(t) \right] \right]$$

therefore the differential equation is:

$$\dot{T}_p + \frac{1}{R_{conv} C_p} T_p = \frac{1}{C_p} Q_{heater} + \frac{1}{R_{conv} C_p} T_a$$

This is a linear, first-order, ordinary differential equation with constant coefficients. The time constant is $\boldsymbol{\tau = R_{conv} C_p}$ and the inputs are $\mathbf{Q_{heater}(t)}$ and $\mathbf{T_a}$. We will be controlling $\mathbf{Q_{heater}(t)}$ with the applied current to the heater $\mathbf{I_{heater}(t)}$. As seen above, this is a nonlinear function but we can consider that the sinusoidal controlling current will be quasi-constant i.e. it will have a nominal value to compensate for the convective heat loss to ambient with some small variation about this value.

Determining The Parameters For The Model

As discussed above, techniques exist to estimate the thermal resistance due to free convection from a flat plate. For this system, this parameter will be determined experimentally. Figure 9 is a measured step response of the system to a voltage step of 20 V for the resistive heater. In the figure, oscilloscope probe 1 was connected to the output of the sensor circuit shown in Figure 5 and oscilloscope probe 2 was connected to the applied voltage to the heater.

The sensor voltage started at 0.046 V and settled at 0.484 V. The time to reach one time constant $\boldsymbol{\tau}$ (i.e. the time to reach 63.2% of the final value) was 266.0 sec as shown in the oscilloscope trace (note the cursers). The thermal capacitance $\mathbf{C_p}$ can be computed as the product of the mass of the aluminum plate **M** (where M = ρ Vol where ρ is the density and Vol is the volume) and the specific heat of aluminum $\boldsymbol{\sigma}$. Using the data for aluminum shown in table 3 for the 2 in by 2 in by 0.06 in plate, the thermal capacitance is:

$$\begin{aligned} C_p &= M\sigma = \rho \ \mathrm{Vol} \ \sigma = 2770.0\,\mathrm{kg/m^3} * 3.93\mathrm{e{-}6}\,\mathrm{m^3} * 875.0 \ \mathrm{J/(kg\text{-}{}^0C)} \\ &= 9.53 \ \mathrm{J/{}^0C} \end{aligned}$$

and the convective resistance is:

$$R_{conv} \;=\; \frac{\tau}{C_p} \;=\; \frac{266.0\,\text{sec}}{9.53\;\text{J}\,/\,{}^0\text{C}} \;=\; 27.9\;{}^0\text{C}\,/\,\text{W}$$

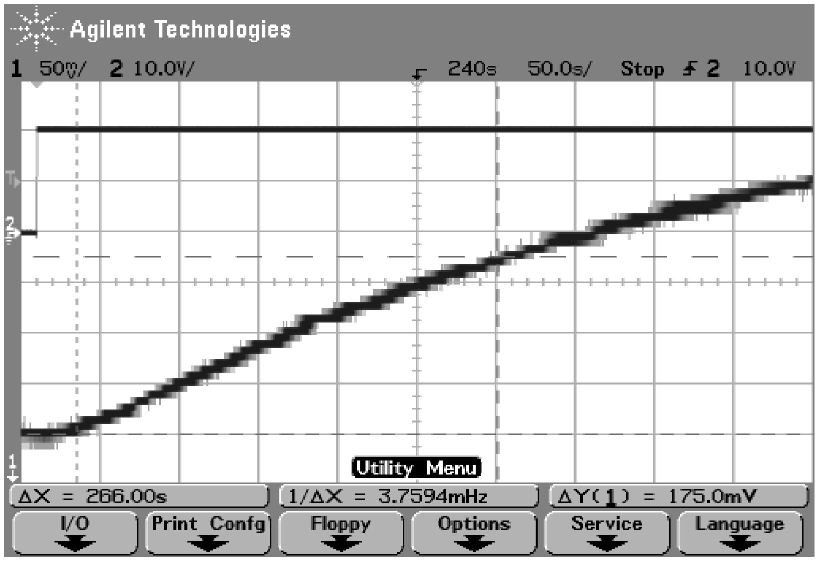

Figure 9. Measured Step Response of the System

Predicted Dynamic Response

In order to predict the dynamic response of the physical system (as represented by the physical model), we must solve the mathematical equations either analytically or numerically. To gain the most complete insight into the dynamic behavior of the physical system, both methods of solution should be used, if possible.

At the operating point of the thermal system

$$T_p\,(t) \,=\, \overline{T}_p \qquad\qquad Q_{heater}\,(t) \,=\, \overline{Q}_{heater} \qquad\qquad \dot{T}_p \,=\, 0$$

and the system differential equation

$$\dot{T}_p \;+\; \frac{1}{R_{conv}\;C_p}\;T_p \;\;=\;\; \frac{1}{C_p}\;Q_{heater} \;+\; \frac{1}{R_{conv}\;C_p}\;T_a$$

reduces to

$$\frac{1}{R_{conv}\ C_p}\ \overline{T}_p = \frac{1}{C_p}\ \overline{Q}_{heater} + \frac{1}{R_{conv}\ C_p}\ T_a$$

$$\overline{T}_p = R_{conv}\ \overline{Q}_{heater} + T_a$$

When the system is in equilibrium, the temperature of the thermal capacitance is constant, and the heat flow rate Q_{heater} supplied by the heater must equal the rate of heat flow through the convective thermal resistance. This should also be apparent by referring to the circuit shown in Figure 8. Therefore, the temperature difference across the resistance is $R_{conv}\ Q_{heater}$.

Define incremental variables:

$$\hat{T}_p(t) = T_p(t) - \overline{T}_p \qquad\qquad \hat{Q}_{heater}(t) = Q_{heater}(t) - \overline{Q}_{heater}$$

Therefore,

$$\dot{\hat{T}}_p + \frac{1}{R_{conv}\ C_p}\left(\hat{T}_p + \overline{T}_p\right) = \frac{1}{C_p}\left(\hat{Q}_{heater} + \overline{Q}_{heater}\right) + \frac{1}{R_{conv}\ C_p}\ T_a$$

$$\dot{\hat{T}}_p + \frac{1}{R_{conv}\ C_p}\ \hat{T}_p = \frac{1}{C_p}\ \hat{Q}_{heater}$$

This is the differential equation that must be controlled.

Observations:

- If $\overline{Q}_{heater} > 0$ then $\overline{T}_p > T_a$ and the plate is being heated.
- If $\overline{Q}_{heater} < 0$ then $\overline{T}_p < T_a$ and the plate is being cooled.
- If $\overline{Q}_{heater} = 0$ then the nominal plate temperature is $\overline{T}_p = T_a$ and $\hat{Q}_{heater}(t) \approx Q_{heater}(t)$.

Since the heater can only produce positive heat flux, the plate can be heated but it must cool by the heat loss to ambient through convection. This is a typical situation for thermal systems and limits the response time of the system. Essentially, you want to prevent the plate temperature from overshooting the desired value because an excessive amount of time would be required to let it cool. All that the fan can do is change the convective heat transfer coefficient from free convection to forced convection making the loss to ambient faster.

To form the transfer function, we will take the Laplace transform of the differential equation:

$$s\,\hat{T}_p(s) + \frac{1}{R_{conv}\;C_p}\,\hat{T}_p(s) = \frac{1}{C_p}\,\hat{Q}_{heater}(s)$$

$$\frac{\hat{T}_p(s)}{\hat{Q}_{heater}(s)} = \frac{\frac{1}{C_p}}{s + \frac{1}{R_{conv}\;C_p}} = \frac{R_{conv}}{\left(R_{conv}\;C_p\right)\;s + 1} = \frac{R_{conv}}{\tau\,s + 1}$$

where $\tau = R_{conv}\;C_p$

This differential equation is a standard first-order, linear, ordinary differential equation with constant coefficients. Step response and frequency response plots for this system are shown in Figure 10.

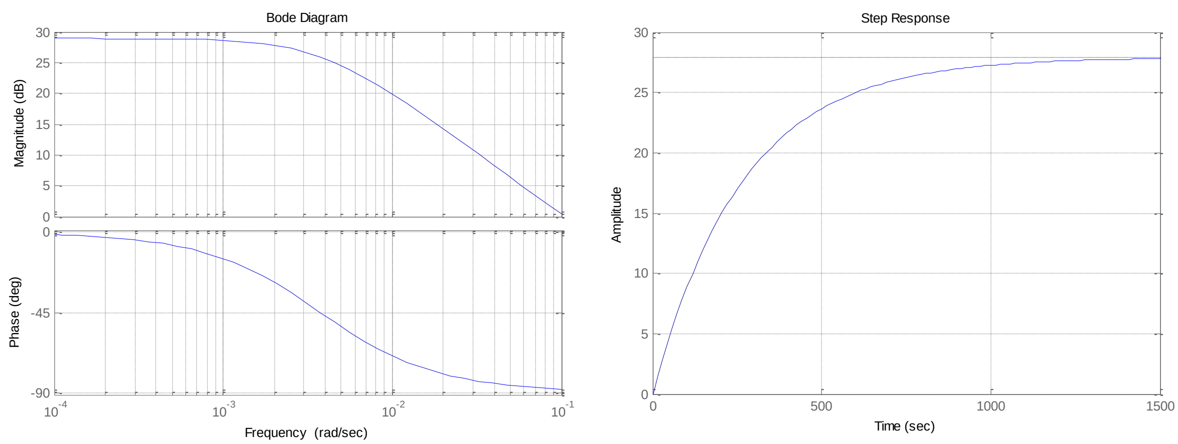

Figure 10. Step Response and Frequency Response Plots for Thermal System

Control System Design

With an understanding of the nature of the system dynamic behavior, as well as a model that predicts reasonably well the performance of the system, it is now necessary to design a control system that will regulate the temperature of the plate. The control system proposed for this experiment is an On/Off controller for both the heater and the fan. The architecture of this control method is discussed here.

Case Study Requirements

Closed-Loop Control of the Plate Temperature

In this case study, the microcontroller will implement only 1 function. In other words, there will be no switching of modes as in the on-off control (solenoid) case study. The goal of this case study is to implement digital control to regulate the temperature of the plate about a desired setpoint. The microcomputer will perform only this function. A switch will be used to start and stop the control. This is illustrated in the following flow chart.

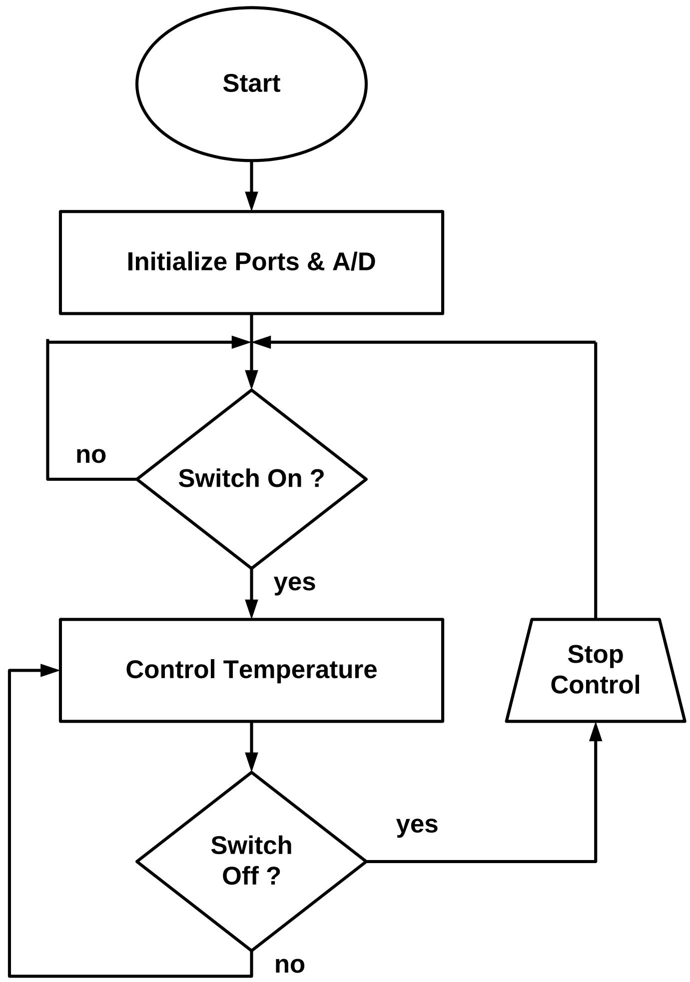

Figure 11. Flow Chart of Control Program

You will build the microcomputer circuit on your protoboard. The interface circuit will be provided. Two port pins on the microcomputer will be used to turn on the heater and the fan. These pins will control a triac which will apply the a.c. current. The flow chart which describes the control program is shown below.

This program will operate with hysteresis (think about the operation of a thermostat in a home heating system). When the plate temperature is below a certain value (5^0C below the setpoint), the heater is turned on. When the plate temperature is above a certain value (5^0C above the setpoint) the fan is turned on. Between these values, nothing changes.

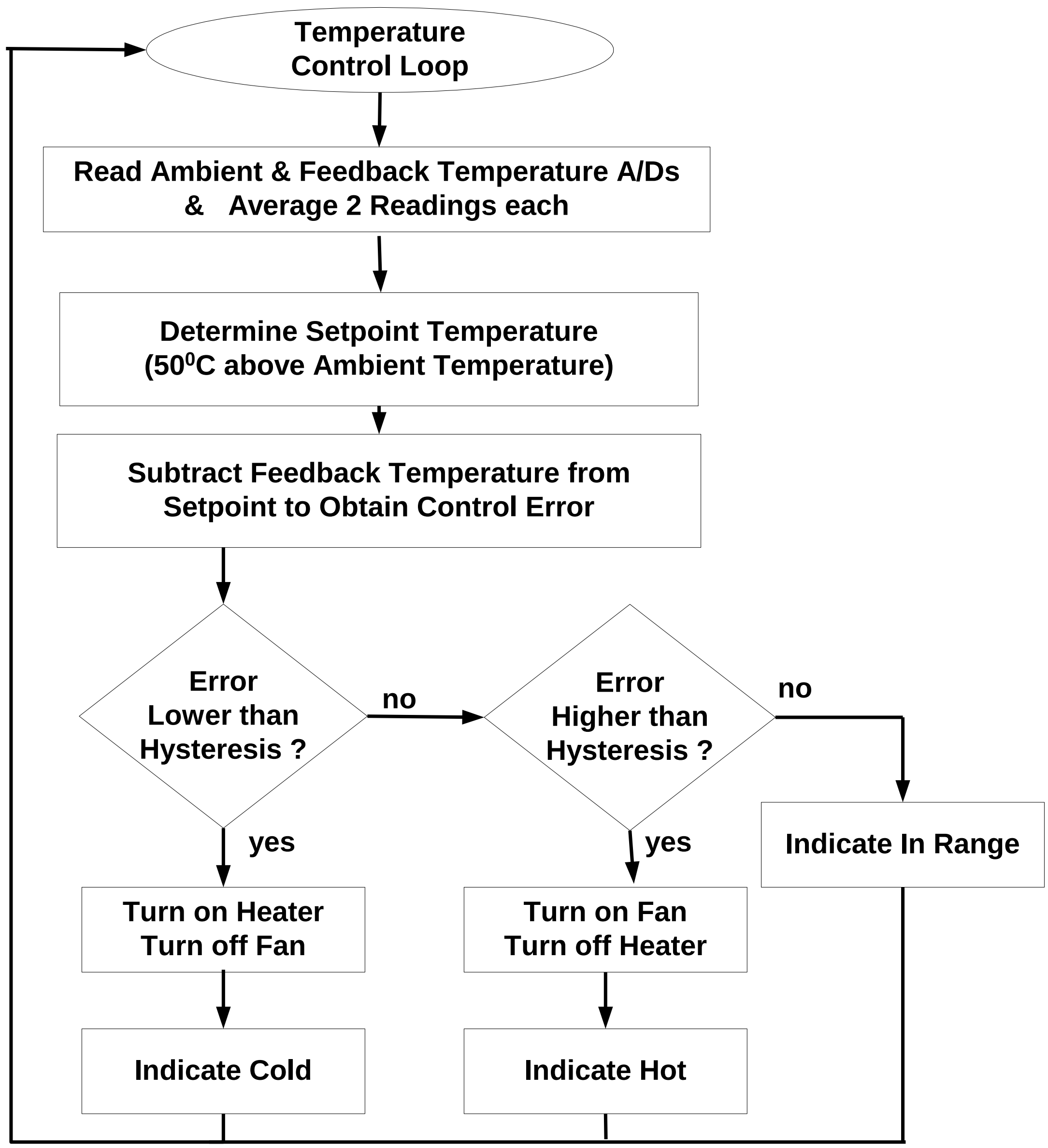

Figure 12. Flow Chart of Control Loop

Laboratory Procedure:

General procedure:

Assume nothing
Using the multimeter, measure all resistors and capacitors. Note values. Note tolerances.
□□Using the multimeter, check +5 V on the power supply.
Using the multimeter, check the connectivity on the protoboard.

The following circuit will be constructed on the protoboard. You must determine which pins on the microcomputer you will use for the on/off switch, the signal to turn on the heater, the signal to turn on the fan the temperature readings (and temperature reference) and the LEDs. You need a clock for this chip to operate and it is good practice to include a reset switch to reset the processor without turning off the power supply. The 3 LEDs will indicate the temperature range of the plate temperature.

Remember to add the 10 μF polarized capacitor and the 0.1 μF capacitor near where the power supply enters the protoboard.

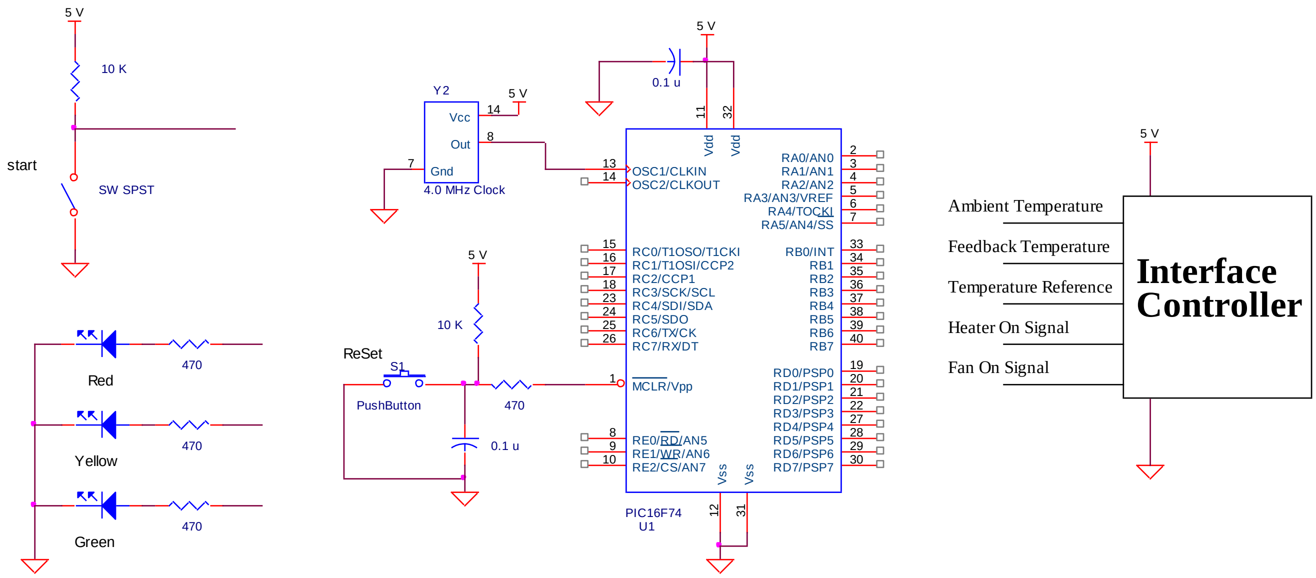

Figure 13. Heater Control Circuit

The wires that will connect your circuit on the protoboard to the temperature interface controller are color coded. The color codes for the various signals are shown below.

White	Heater Control
Yellow	Fan Control
Green	Plate Temperature
Blue	Ambient Temperature
Orange	Voltage Reference
Red	+ 5 V
Black	Ground

wires

Figure 14. Heater Control Connector

General Programming Considerations

The control program will be programmed in Assembly. In general, the embedded program will operate as follows:

The ports and A/D module have to be initialized.

When the toggle switch is off (port pin Hi), the control is started. When the toggle switch is on (port pin Lo), the control is stopped. If when you start the control the temperature is in the control band, do nothing.

Several registers have to be declared. One will hold the ambient temperature and another will hold the present plate temperature (as measured by the A/D and found in the register ADRES). Two readings of the ambient sensor and two readings of the plate sensor are averaged before proceeding. (Averaging is done to remove noise and make the reading a better representation of temperature so you should read one sensor, then read the second, then take the second reading of the first sensor, then take the second reading of the second sensor. It does not matter which sensor is read first.)

The setpoint for the control will be calculated to be 50^0C above the averaged ambient temperature. The present average plate temperature is subtracted from the setpoint to form the control system error. This error is used to determine whether or not the heater or fan has to be turned on with a 5^0C hysteresis band. If the error is within the hysteresis band, a yellow indicator LED is turned on. If the error is below the hysteresis band, a green indicator LED is turned on. If the error is above the hysteresis band, a red indicator LED is turned on. Note that when the system is working, either the heater or the fan (and not both) should be on. The plate temperature will cycle up and down in the hysteresis band. This is illustrated in Figure 15. In control terminology, this is called limit cycling and is a characteristic of on-off control. Almost all temperature control systems exhibit some limit cycling.

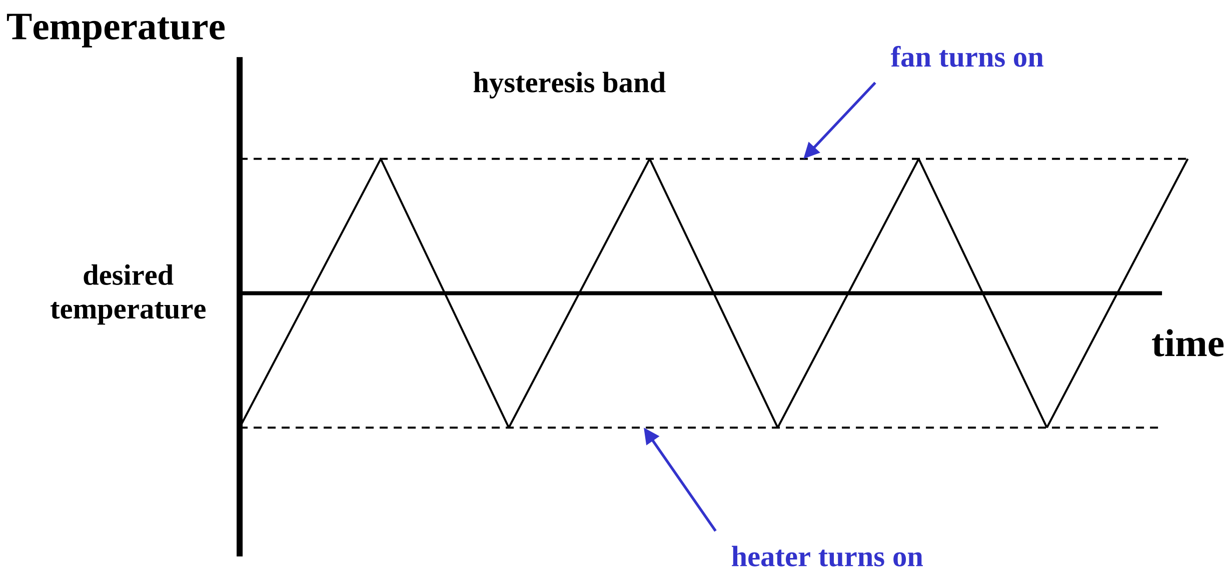

Figure 15. Illustration of How the Temperature Will Cycle During Operation

VERY Important Note: The output of the microcomputer must be LO to turn on the heater or fan.

Hint: The following is the way to think about the two temperature readings:

Recall that when you program in Assembly, you have to keep in mind what the numbers in the registers mean. The microcomputer does not care. Assume that the room temperature is 25^0C. Use the equation for the AD22100 and determine what the code will be in the A/D register ADRES. Remember that the reference is 4.096 V so the code will be:

AD22100 Voltage * 255 / 4.096 V

Next determine what the voltage from the AD590 contacting the plate will be at 80^0C (which is the point where the fan must turn on and the heater turn off $\Rightarrow$ ambient + 50^0C + 5^0C hysteresis). Determine what the code in the A/D register ADRES should be for this.

Do the same thing for 70^0C (which is the point where the fan must turn off and the heater turn on $\Rightarrow$ ambient + 50^0C - 5^0C hysteresis). Determine what the code in the A/D register ADRES should be for this.

Now if you do the same process for an ambient temperature of 26^0C, you will see that the number in the A/D converter register for the plate temperatures should go up by roughly twice the difference in the ambient temperature since the gain of the AD590 (34 mV / ^{0}C) is roughly twice the AD22100 (18 mV / ^{0}C).

If you program in the numbers for an ambient temperature of 25^{0}C (or any other value for that matter), you can add or subtract from these numbers if the ambient temperature is different. You have to keep in mind what these numbers mean. The microcomputer does not care. (Be sure to add comments so I can follow your code.)

Questions:

a) Why should the plate require time to heat up?
b) Would you expect the temperature of the top of the plate (exposed to ambient air) and the bottom of the plate (attached to the heater) to be at the same temperature? If they are different, express the difference in terms of some material property of the plate.
c) In the ideal system, if the heater is left on continuously, would the temperature of the plate rise to infinity? If not, what would cause it to stop?
d) Assuming that the equivalent circuit for the heater is simply a resistor and the power is applied from a D.C. power supply, what is the value of the heat flux (in Watts) in terms of the applied voltage to the heater?
e) Assuming that the equivalent circuit for the heater is simply a resistor and the power is applied from the A.C. power line, what is the value of the heat flux (in Watts) in terms of the applied voltage to the heater?
f) Give 2 applications of temperature control in commercial (home or personal) products.
g) Give 2 applications of temperature control in business products or machines (i.e. commercial products used by businesses).
h) Give 2 applications of temperature control in industrial (factory) processes.
i) A potential problem is that the heater can burn out. Describe in words how you might program the microcomputer to detect this problem and declare a fault.
j) Another potential problem is that the temperature sensor can burn out at some fixed value. Describe in words how you might program the microcomputer to detect this problem and declare a fault.

Two-Terminal IC Temperature Transducer

AD590

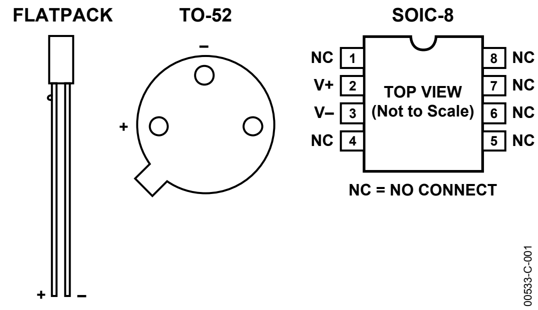

Figure 1. Pin Designations

FEATURES

Linear current output: 1 μA/K
Wide temperature range: −55°C to +150°C
Probe compatible ceramic sensor package
2-terminal device: voltage in/current out
Laser trimmed to ±0.5°C calibration accuracy (AD590M)
Excellent linearity: ±0.3°C over full range (AD590M)
Wide power supply range: 4 V to 30 V
Sensor isolation from case
Low cost

GENERAL DESCRIPTION

The AD590 is a 2-terminal integrated circuit temperature transducer that produces an output current proportional to absolute temperature. For supply voltages between 4 V and 30 V the device acts as a high-impedance, constant current regulator passing 1 μA/K. Laser trimming of the chip's thin-film resistors is used to calibrate the device to 298.2 μA output at 298.2 K (25°C).

The AD590 should be used in any temperature-sensing application below 150°C in which conventional electrical temperature sensors are currently employed. The inherent low cost of a monolithic integrated circuit combined with the elimination of support circuitry makes the AD590 an attractive alternative for many temperature measurement situations. Linearization circuitry, precision voltage amplifiers, resistance measuring circuitry, and cold junction compensation are not needed in applying the AD590.

In addition to temperature measurement, applications include temperature compensation or correction of discrete components, biasing proportional to absolute temperature, flow rate measurement, level detection of fluids and anemometry. The AD590 is available in chip form, making it suitable for hybrid circuits and fast temperature measurements in protected environments.

The AD590 is particularly useful in remote sensing applications. The device is insensitive to voltage drops over long lines due to its high impedance current output. Any well-insulated twisted pair is sufficient for operation at hundreds of feet from the receiving circuitry. The output characteristics also make the AD590 easy to multiplex: the current can be switched by a CMOS multiplexer or the supply voltage can be switched by a logic gate output.

PRODUCT HIGHLIGHTS

1. The AD590 is a calibrated, 2-terminal temperature sensor requiring only a dc voltage supply (4 V to 30 V). Costly transmitters, filters, lead wire compensation, and linearization circuits are all unnecessary in applying the device.

2. State-of-the-art laser trimming at the wafer level in conjunction with extensive final testing ensures that AD590 units are easily interchangeable.

3. Superior interface rejection occurs, because the output is a current rather than a voltage. In addition, power requirements are low (1.5 mWs @ 5 V @ 25°C). These features make the AD590 easy to apply as a remote sensor.

4. The high output impedance (>10 MΩ) provides excellent rejection of supply voltage drift and ripple. For instance, changing the power supply from 5 V to 10 V results in only a 1 μA maximum current change, or 1°C equivalent error.

5. The AD590 is electrically durable: it withstands a forward voltage of up to 44 V and a reverse voltage of 20 V. Therefore, supply irregularities or pin reversal does not damage the device.

Rev. C

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REVISION HISTORY

Revision C

9/03—Data Sheet Changed from REV. B to REV. C.

Added SOIC-8 package ... Universal

Change to Figure 1 ... 1

Updated OUTLINE DIMENSIONS ... 13

Added ORDERING GUIDE ... 14

SPECIFICATIONS

AD590J AND AD590K SPECIFICATIONS

Table 1. @ 25°C and V_S = 5 V unless otherwise noted

	AD590J			AD590K			
Parameter	**Min**	**Typ**	**Max**	**Min**	**Typ**	**Max**	**Unit**
POWER SUPPLY							
Operating Voltage Range	**4**		30	**4**		30	Volts
OUTPUT							
Nominal Current Output @ 25°C (298.2K)		298.2			298.2		μA
Nominal Temperature Coefficient		1			1		μA/K
Calibration Error @ 25°C			**±5.0**			**±2.5**	°C
Absolute Error (over rated performance temperature range)							
Without External Calibration Adjustment			**±10**			**±5.5**	°C
With 25°C Calibration Error Set to Zero			**±3.0**			**±2.0**	°C
Nonlinearity							
For TO-52 and Flatpack packages			**±1.5**			**±0.8**	°C
For 8-Lead SOIC package			**±1.5**			**±1.0**	°C
Repeatability[1]			±0.1			±0.1	°C
Long-Term Drift[2]			±0.1			±0.1	°C
Current Noise		40			40		pA/√Hz
Power Supply Rejection							
4 V ≤ V_S ≤ 5 V		0.5			0.5		μA/V
5 V ≤ V_S ≤ 15 V		0.2			0.2		μV/V
15 V ≤ V_S ≤ 30 V		0.1			0.1		μA/V
Case Isolation to Either Lead		10^{10}			10^{10}		Ω
Effective Shunt Capacitance		100			100		pF
Electrical Turn-On Time		20			20		μs
Reverse Bias Leakage Current[3]							
(Reverse Voltage = 10 V)		10			10		pA

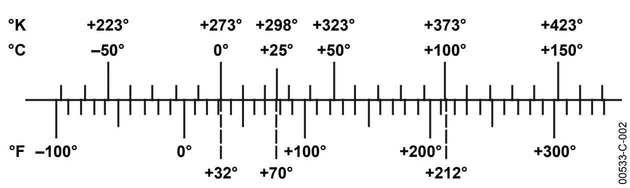
[1] Maximum deviation between +25°C readings after temperature cycling between −55°C and +150°C; guaranteed, not tested.
[2] Conditions: constant 5 V, constant 125°C; guaranteed, not tested.
[3] Leakage current doubles every 10°C.
Specifications shown in **boldface** are tested on all production units at final electrical test. Results from those tests are used to calculate outgoing quality levels. All min and max specifications are guaranteed, although only those shown in **boldface** are tested on all production units.

AD590L AND AD590M SPECIFICATIONS

Table 2. @ 25°C and V_S = 5 V unless otherwise noted

Parameter	AD590L Min	AD590L Typ	AD590L Max	AD590M Min	AD590M Typ	AD590M Max	Unit
POWER SUPPLY							
Operating Voltage Range	**4**		30	**4**		30	Volts
OUTPUT							
Nominal Current Output @ 25°C (298.2K)		298.2			298.2		µA
Nominal Temperature Coefficient		1			1		µA/K
Calibration Error @ +25°C			**±1.0**			**±0.5**	°C
Absolute Error (over rated performance temperature range)							°C
Without External Calibration Adjustment			**±3.0**			**±1.7**	°C
With ± 25°C Calibration Error Set to Zero			**±1.6**			**±1.0**	°C
Nonlinearity			**±0.4**			**±0.3**	°C
Repeatability[1]			±0.1			±0.1	°C
Long-Term Drift[2]			±0.1			±0.1	°C
Current Noise		40			40		pA/√Hz
Power Supply Rejection							
4 V ≤ V_S ≤ 5 V		0.5			0.5		µA/V
5 V ≤ V_S ≤ 15 V		0.2			0.2		µA/V
15 V ≤ V_S ≤ 30 V		0.1			0.1		µA/V
Case Isolation to Either Lead		10^{10}			10^{10}		Ω
Effective Shunt Capacitance		100			100		pF
Electrical Turn-On Time		20			20		µs
Reverse Bias Leakage Current[3]							
(Reverse Voltage = 10 V)		10			10		pA

[1] Maximum deviation between +25°C readings after temperature cycling between –55°C and +150°C; guaranteed, not tested.
[2] Conditions: constant 5 V, constant 125°C; guaranteed, not tested.
[3] Leakage current doubles every 10°C.
Specifications shown in **boldface** are tested on all production units at final electrical test. Results from those tests are used to calculate outgoing quality levels. All min and max specifications are guaranteed, although only those shown in **boldface** are tested on all production units.



$$^\circ C = \frac{5}{9}\left(^\circ F - 32\right) \quad K = {^\circ C} + 273.15$$

$$^\circ F = \frac{9}{5}\left(^\circ C + 32\right) \quad {^\circ R} = {^\circ F} + 459.7$$

Figure 2. Temperature Scale Conversion Equations

ABSOLUTE MAXIMUM RATINGS

Table 3.

Parameter	Rating
Forward Voltage (E+ or E–)	44 V
Reverse Voltage (E+ to E–)	−20 V
Breakdown Voltage (Case E+ or E–)	±200 V
Rated Performance Temperature Range[1]	−55°C to +150°C
Storage Temperature Range[1]	−65°C to +155°C
Lead Temperature (Soldering, 10 sec)	300°C

[1]The AD590 has been used at –100°C and +200°C for short periods of measurement with no physical damage to the device. However, the absolute errors specified apply to only the rated performance temperature range.

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

ESD 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 this product 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.

WARNING!

ESD SENSITIVE DEVICE

PRODUCT DESCRIPTION

The AD590H has 60 μ inches of gold plating on its Kovar leads and Kovar header. A resistance welder is used to seal the nickel cap to the header. The AD590 chip is eutectically mounted to the header and ultrasonically bonded to with 1 mil aluminum wire. Kovar composition: 53% iron nominal; 29% ±1% nickel; 17% ±1% cobalt; 0.65% manganese max; 0.20% silicon max; 0.10% aluminum max; 0.10% magnesium max; 0.10% zirconium max; 0.10% titanium max; 0.06% carbon max.

The AD590F is a ceramic package with gold plating on its Kovar leads, Kovar lid, and chip cavity. Solder of 80/20 Au/Sn composition is used for the 1.5 mil thick solder ring under the lid. The chip cavity has a nickel underlay between the metallization and the gold plating. The AD590 chip is eutectically mounted in the chip cavity at 410°C and ultrasonically bonded to with 1 mil aluminum wire. Note that the chip is in direct contact with the ceramic base, not the metal lid. When using the AD590 in die form, the chip substrate must be kept electrically isolated (floating) for correct circuit operation.

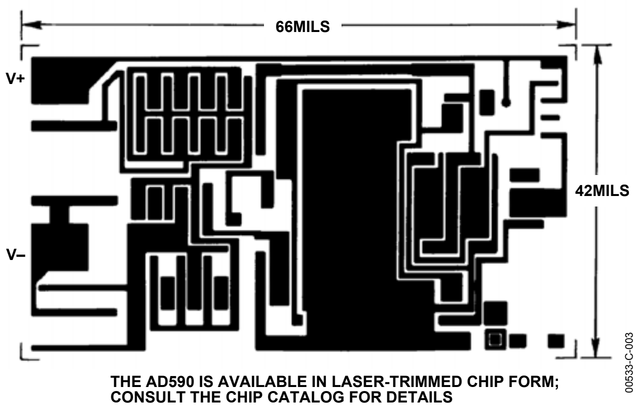


Figure 3. Metalization Diagram

CIRCUIT DESCRIPTION[1]

The AD590 uses a fundamental property of the silicon transistors from which it is made to realize its temperature proportional characteristic: if two identical transistors are operated at a constant ratio of collector current densities, r, then the difference in their base-emitter voltage will be (kT/q)(In r). Since both k (Boltzman's constant) and q (the charge of an electron) are constant, the resulting voltage is directly proportional to absolute temperature (PTAT).

In the AD590, this PTAT voltage is converted to a PTAT current by low temperature coefficient thin-film resistors. The total current of the device is then forced to be a multiple of this PTAT current. Figure 4 is the schematic diagram of the AD590. In this figure, Q8 and Q11 are the transistors that produce the PTAT voltage. R5 and R6 convert the voltage to current. Q10, whose collector current tracks the collector currents in Q9 and Q11, supplies all the bias and substrate leakage current for the rest of the circuit, forcing the total current to be PTAT. R5 and R6 are laser-trimmed on the wafer to calibrate the device at 25°C.

Figure 5 shows the typical V–I characteristic of the circuit at 25°C and the temperature extremes.

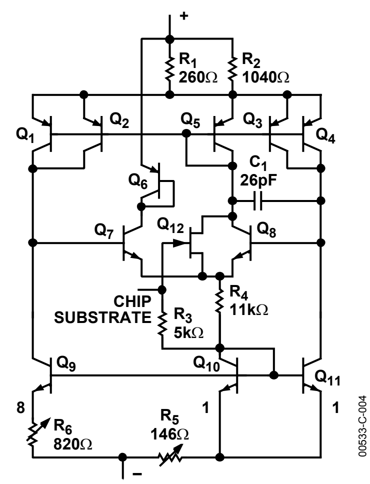


Figure 4. Schematic Diagram

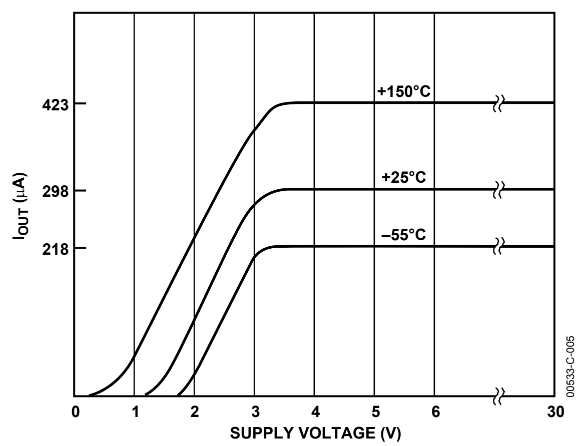


Figure 5. V-1 Plot

EXPLANATION OF TEMPERATURE SENSOR SPECIFICATIONS

The way in which the AD590 is specified makes it easy to apply in a wide variety of applications. It is important to understand the meaning of the various specifications and the effects of supply voltage and thermal environment on accuracy.

[1] For a more detailed description, see M.P. Timko, "A Two-Terminal IC Temperature Transducer," IEEE J. Solid State Circuits, Vol. SC-11, p. 784-788, Dec. 1976. Understanding the Specifications–AD590.

The AD590 is basically a PTAT (proportional to absolute temperature)[1] current regulator. That is, the output current is equal to a scale factor times the temperature of the sensor in degrees Kelvin. This scale factor is trimmed to 1 μA/K at the factory, by adjusting the indicated temperature (that is, the output current) to agree with the actual temperature. This is done with 5 V across the device at a temperature within a few degrees of 25°C (298.2K). The device is then packaged and tested for accuracy over temperature.

CALIBRATION ERROR

At final factory test, the difference between the indicated temperature and the actual temperature is called the calibration error. Since this is a scale factory error, its contribution to the total error of the device is PTAT. For example, the effect of the 1°C specified maximum error of the AD590L varies from 0.73°C at −55°C to 1.42°C at 150°C. Figure 6 shows how an exaggerated calibration error would vary from the ideal over temperature.

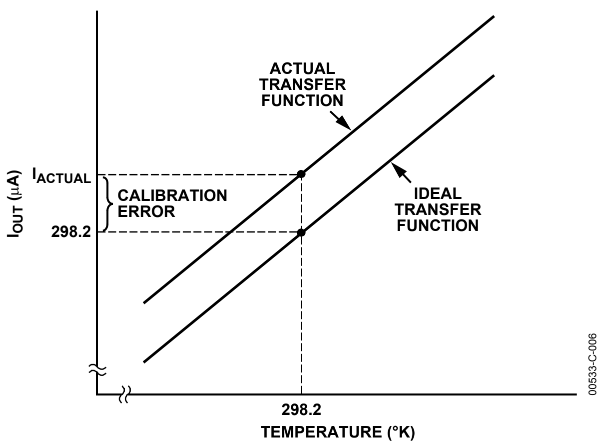


Figure 6. Calibration Error vs. Temperature

The calibration error is a primary contributor to maximum total error in all AD590 grades. However, since it is a scale factor error, it is particularly easy to trim. Figure 7 shows the most elementary way of accomplishing this. To trim this circuit, the temperature of the AD590 is measured by a reference temperature sensor and R is trimmed so that V_T = 1 mV/K at that temperature. Note that when this error is trimmed out at one temperature, its effect is zero over the entire temperature range. In most applications there is a current-to-voltage conversion resistor (or, as with a current input ADC, a reference) that can be trimmed for scale factor adjustment.

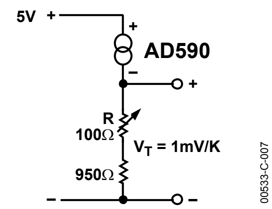


Figure 7. One Temperature Trim

ERROR VERSUS TEMPERATURE: WITH CALIBRATION ERROR TRIMMED OUT

Each AD590 is tested for error over the temperature range with the calibration error trimmed out. This specification could also be called the "variance from PTAT," because it is the maximum difference between the actual current over temperature and a PTAT multiplication of the actual current at 25°C. This error consists of a slope error and some curvature, mostly at the temperature extremes. Figure 8 shows a typical AD590K temperature curve before and after calibration error trimming.

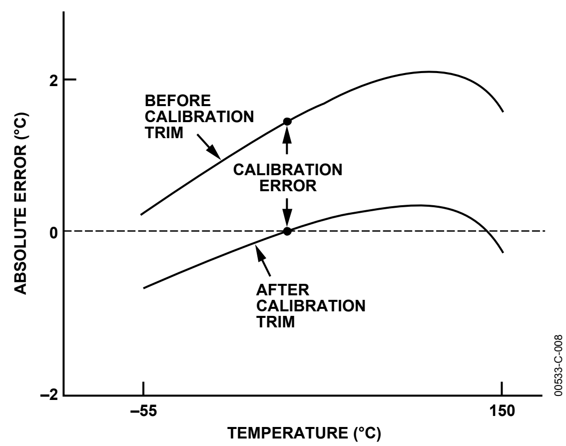


Figure 8. Effect to Scale Factor Trim on Accuracy

ERROR VERSUS TEMPERATURE: NO USER TRIMS

Using the AD590 by simply measuring the current, the total error is the variance from PTAT, described above, plus the effect of the calibration error over temperature. For example, the AD590L maximum total error varies from 2.33°C at −55°C to 3.02°C at 150°C. For simplicity, only the large figure is shown on the specification page.

NONLINEARITY

Nonlinearity as it applies to the AD590 is the maximum deviation of current over temperature from a best-fit straight line. The nonlinearity of the AD590 over the −55°C to +150°C range is superior to all conventional electrical temperature sensors such as thermocouples, RTDs, and thermistors. Figure 9 shows the nonlinearity of the typical AD590K from Figure 8.

[1] T(°C) = T(K) −273.2. Zero on the Kelvin scale is "absolute zero"; there is no lower temperature.

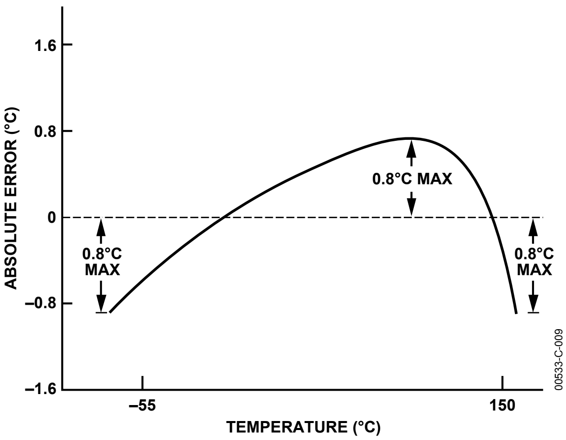


Figure 9. Nonlinearity

Figure 10 shows a circuit in which the nonlinearity is the major contributor to error over temperature. The circuit is trimmed by adjusting R1 for a 0 V output with the AD590 at 0°C. R2 is then adjusted for 10 V out with the sensor at 100°C. Other pairs of temperatures may be used with this procedure as long as they are measured accurately by a reference sensor. Note that for 15 V output (150°C) the V+ of the op amp must be greater than 17 V. Also note that V− should be at least −4 V; if V− is ground, there is no voltage applied across the device.

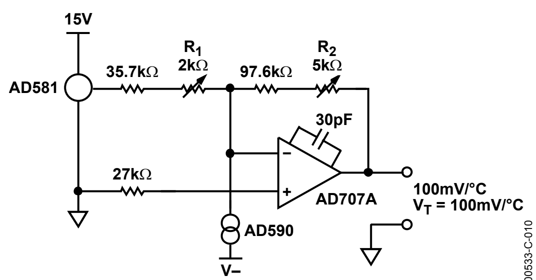


Figure 10. 2-Temperature Trim

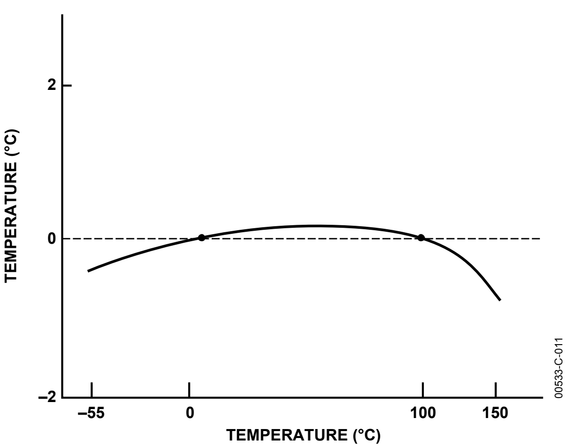


Figure 11. Typical 2-Trim Accuracy

VOLTAGE AND THERMAL ENVIRONMENT EFFECTS

The power supply rejection specifications show the maximum expected change in output current versus input voltage changes. The insensitivity of the output to input voltage allows the use of unregulated supplies. It also means that hundreds of ohms of resistance (such as a CMOS multiplexer) can be tolerated in series with the device.

It is important to note that using a supply voltage other than 5 V does not change the PTAT nature of the AD590. In other words, this change is equivalent to a calibration error and can be removed by the scale factor trim (see Figure 8).

The AD590 specifications are guaranteed for use in a low thermal resistance environment with 5 V across the sensor. Large changes in the thermal resistance of the sensor's environment change the amount of self-heating and result in changes in the output, which are predictable but not necessarily desirable.

The thermal environment in which the AD590 is used determines two important characteristics: the effect of self-heating and the response of the sensor with time. Figure 12 is a model of the AD590 that demonstrates these characteristics.

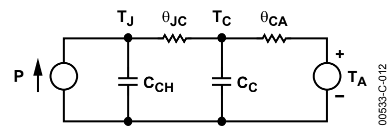


Figure 12. Thermal Circuit Model

As an example, for the TO-52 package, θ_{JC} is the thermal resistance between the chip and the case, about 26°C/W. θ_{CA} is the thermal resistance between the case and the surroundings and is determined by the characteristics of the thermal connection. Power source P represents the power dissipated on the chip. The rise of the junction temperature, T_J, above the ambient temperature T_A is

$$T_J - T_A = P(\theta_{JC} + \theta_{CA})$$

Equation 1.

Table 4 gives the sum of θ_{JC} and θ_{CA} for several common thermal media for both the H and F packages. The heat sink used was a common clip-on. Using Equation 1, the temperature rise of an AD590 H package in a stirred bath at 25°C, when driven with a 5 V supply, is 0.06°C. However, for the same conditions in still air, the temperature rise is 0.72°C. For a given supply voltage, the temperature rise varies with the current and is PTAT. Therefore, if an application circuit is trimmed with the sensor in the same thermal environment in which it will be used, the scale factor trim compensates for this effect over the entire temperature range.

Table 4. Thermal Resistance

Medium	$\theta_{JC} + \theta_{CA}$ (°C/Watt)		τ (sec)[1]	
	H	F	H	F
Aluminum Block	30	10	0.6	0.1
Stirred Oil[2]	42	60	1.4	0.6
Moving Air[3]				
With Heat Sink	45	–	5.0	–
Without Heat Sink	115	190	13.5	10.0
Still Air				
With Heat Sink	191	–	108	–
Without Heat Sink	480	650	60	30

[1]τ is dependent upon velocity of oil; average of several velocities listed above.
[2]Air velocity @ 9 ft/sec.
[3]The time constant is defined as the time required to reach 63.2% of an instantaneous temperature change.

The time response of the AD590 to a step change in temperature is determined by the thermal resistances and the thermal capacities of the chip, C_{CH}, and the case, C_C. C_{CH} is about 0.04 Ws/°C for the AD590. C_C varies with the measured medium, because it includes anything that is in direct thermal contact with the case. The single time constant exponential curve of Figure 13 is usually sufficient to describe the time response, T (t). Table 4 shows the effective time constant, τ, for several media.

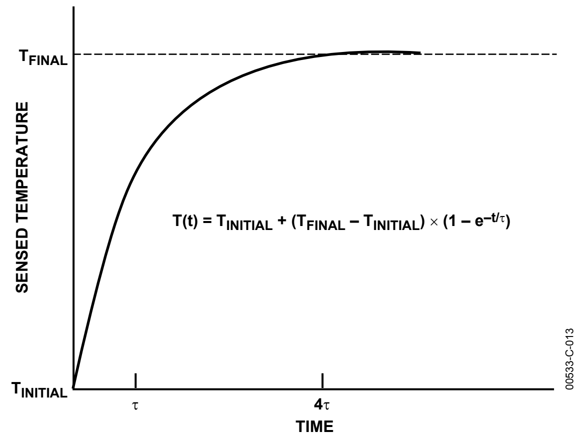


Figure 13. Time Response Curve

GENERAL APPLICATIONS

Figure 14 demonstrates the use of a low cost digital panel meter for the display of temperature on either the Kelvin, Celsius, or Fahrenheit scales. For Kelvin temperature, Pins 9, 4, and 2 are grounded; for Fahrenheit temperature, Pins 4 and 2 are left open.

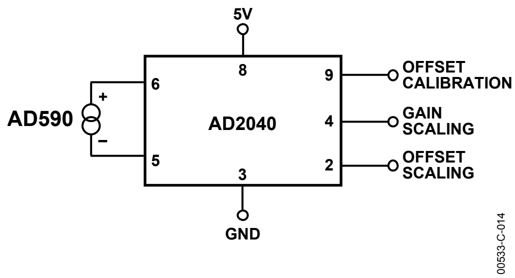


Figure 14. Variable Scale Display

The above configuration yields a 3-digit display with 1°C or 1°F resolution, in addition to an absolute accuracy of ±2.0°C over the −55°C to +125°C temperature range, if a one-temperature calibration is performed on an AD590K, AD590L, or AD590M.

Connecting several AD590 units in series as shown in Figure 15 allows the minimum of all the sensed temperatures to be indicated. In contrast, using the sensors in parallel yields the average of the sensed temperatures.

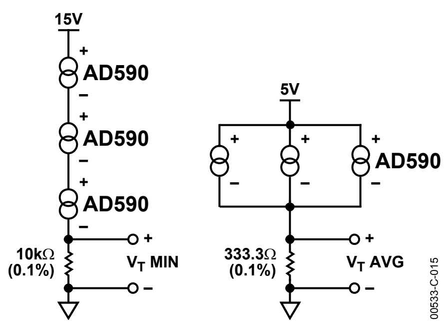


Figure 15. Series and Parallel Connection

The circuit in Figure 16 demonstrates one method by which differential temperature measurements can be made. R1 and R2 can be used to trim the output of the op amp to indicate a desired temperature difference. For example, the inherent offset between the two devices can be trimmed in. If V+ and V− are radically different, then the difference in internal dissipation causes a differential internal temperature rise. This effect can be used to measure the ambient thermal resistance seen by the sensors in applications such as fluid-level detectors or anemometry.

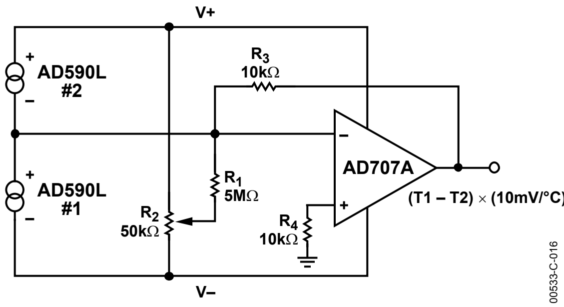


Figure 16. Differential Measurements

Figure 17 is an example of a cold junction compensation circuit for a Type J thermocouple using the AD590 to monitor the reference junction temperature. This circuit replaces an ice-bath as the thermocouple reference for ambient temperatures between 15°C and 35°C. The circuit is calibrated by adjusting R_T for a proper meter reading with the measuring junction at a known reference temperature and the circuit near 25°C. Using components with the TCs as specified in Figure 17, compensation accuracy is within ±0.5°C for circuit temperatures between 15°C and 35°C. Other thermocouple types can be accommodated with different resistor values. Note that the TCs of the voltage reference and the resistors are the primary contributors to error.

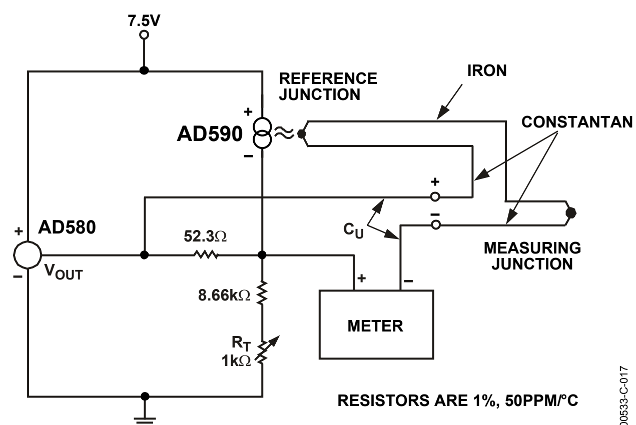


Figure 17. Cold Junction Compensation Circuit for Type J Thermocouple

Figure 18 is an example of a current transmitter designed to be used with 40 V, 1 kΩ systems; it uses its full current range of 4 mA to 20 mA for a narrow span of measured temperatures. In this example, the 1 μA/K output of the AD590 is amplified to 1 mA/°C and offset so that 4 mA is equivalent to 17°C and 20 mA is equivalent to 33°C. R_T is trimmed for proper reading at an intermediate reference temperature. With a suitable choice of resistors, any temperature range within the operating limits of the AD590 may be chosen.

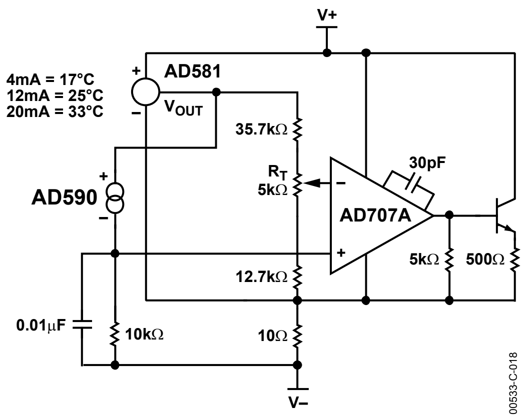


Figure 18. 4 mA to 20 mA Current Transmitter

Figure 19 is an example of a variable temperature control circuit (thermostat) using the AD590. R_H and R_L are selected to set the high and low limits for R_{SET}. R_{SET} could be a simple pot, a calibrated multiturn pot, or a switched resistive divider. Powering the AD590 from the 10 V reference isolates the AD590 from supply variations while maintaining a reasonable voltage (~7 V) across it. Capacitor C_1 is often needed to filter extraneous noise from remote sensors. R_B is determined by the β of the power transistor and the current requirements of the load.

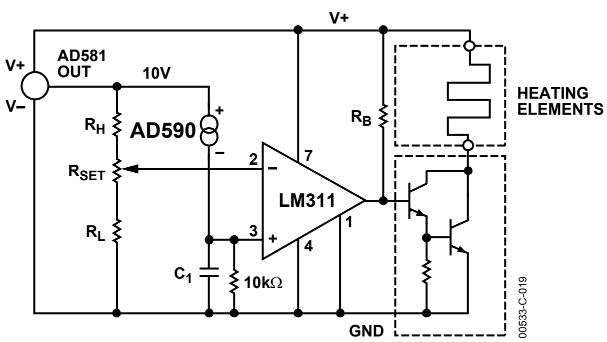


Figure 19. Simple Temperature Control Circuit

Figure 20 shows that the AD590 can be configured with an 8-bit DAC to produce a digitally controlled set point. This particular circuit operates from 0°C (all inputs high) to 51.0°C (all inputs low) in 0.2°C steps. The comparator is shown with 1.0°C hysteresis, which is usually necessary to guard-band for extraneous noise. Omitting the 5.1 MΩ resistor results in no hysteresis.

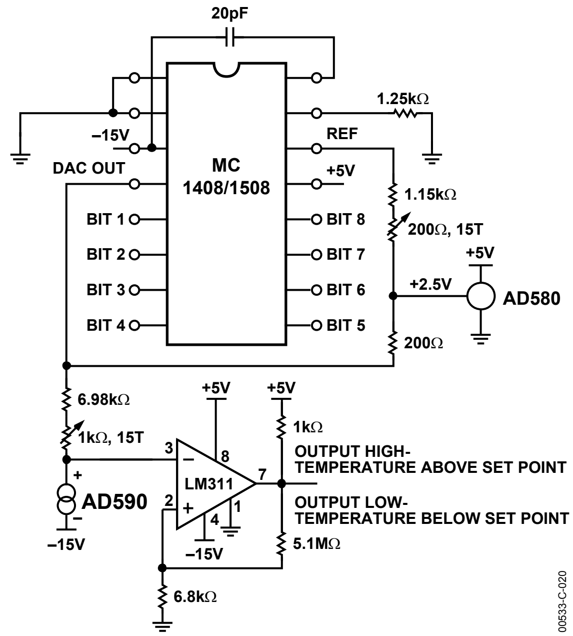


Figure 20. DAC Set Point

The voltage compliance and the reverse blocking characteristic of the AD590 allows it to be powered directly from 5 V CMOS logic. This permits easy multiplexing, switching, or pulsing for minimum internal heat dissipation. In Figure 21, any AD590 connected to a logic high passes a signal current through the current measuring circuitry, while those connected to a logic zero pass insignificant current. The outputs used to drive the AD590s may be employed for other purposes, but the additional capacitance due to the AD590 should be taken into account.

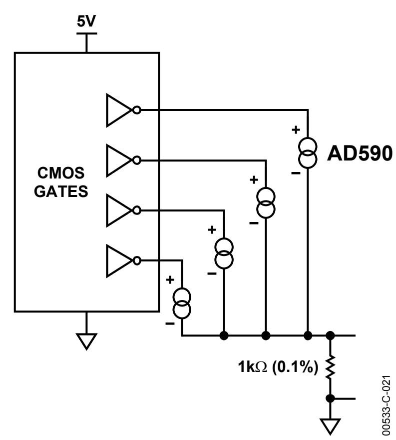


Figure 21. AD590 Driven from CMOS Logic

CMOS analog multiplexers can also be used to switch AD590 current. Due to the AD590's current mode, the resistance of such switches is unimportant as long as 4 V is maintained across the transducer. Figure 22 shows a circuit that combines the principle demonstrated in Figure 21 with an 8-channel CMOS multiplexer. The resulting circuit can select 1–80 sensors over only 18 wires with a 7-bit binary word.

The inhibit input on the multiplexer turns all sensors off for minimum dissipation while idling.

Figure 23 demonstrates a method of multiplexing the AD590 in the two-trim mode (see Figure 10 and Figure 11). Additional AD590s and their associated resistors can be added to multiplex up to eight channels of ±0.5°C absolute accuracy over the temperature range of −55°C to +125°C. The high temperature restriction of 125°C is due to the output range of the op amps; output to 150°C can be achieved by using a 20 V supply for the op amp.

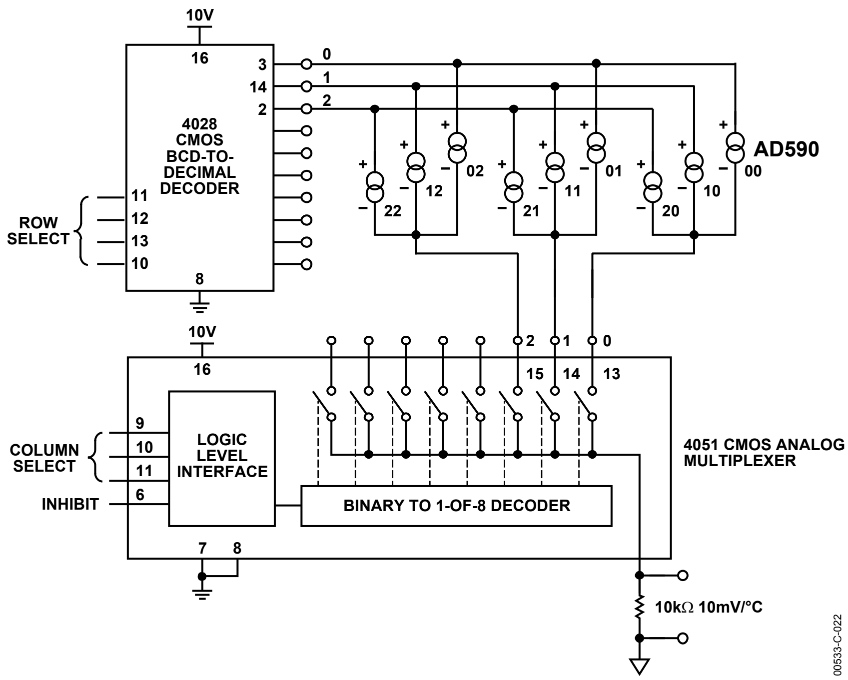


Figure 22. Matrix Multiplexer

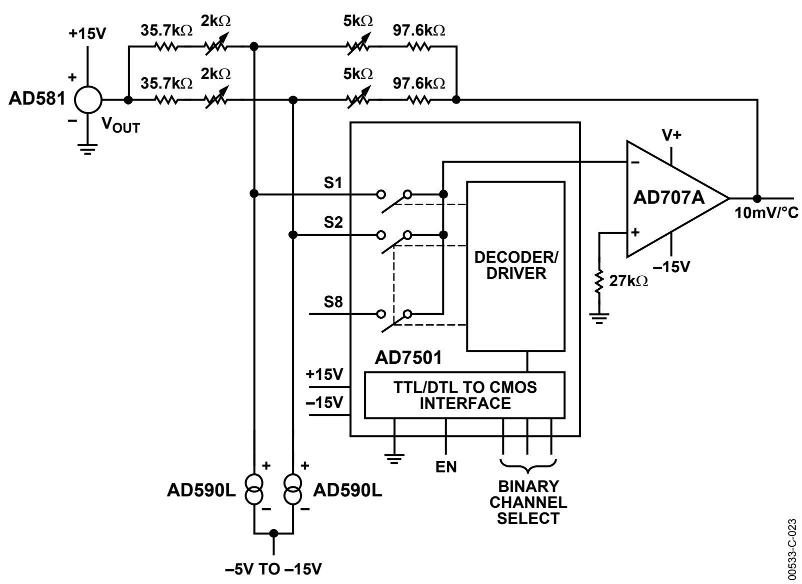


Figure 23. 8-Channel Multiplexer

OUTLINE DIMENSIONS

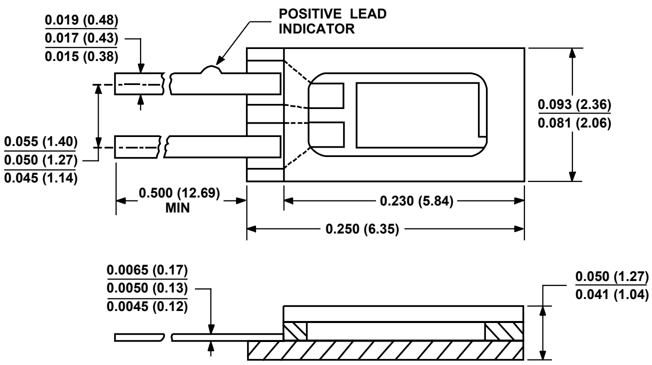
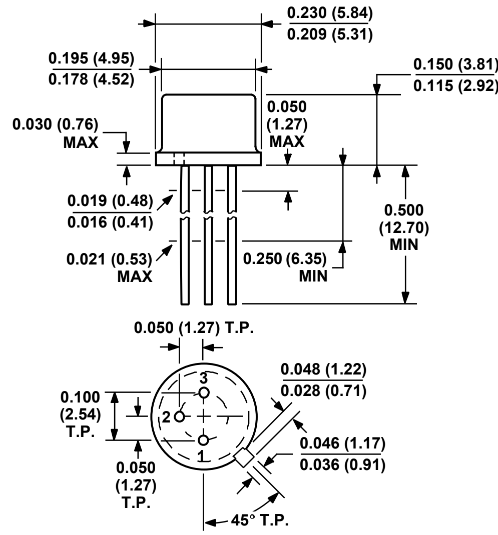
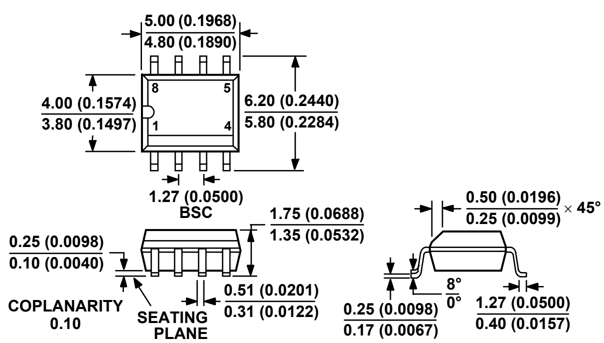


Figure 24. 2-Lead Ceramic Flat Package [CQFP]
(F-2)
Dimensions shown in inches and (millimeters)



CONTROLLING DIMENSIONS ARE IN INCHES; MILLIMETERS DIMENSIONS (IN PARENTHESES) ARE ROUNDED-OFF INCH EQUIVALENTS FOR REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN

Figure 25. 3-Pin Metal Header Package [TO-52]
(H-03)
Dimensions shown in inches and (millimeters)



COMPLIANT TO JEDEC STANDARDS MS-012AA
CONTROLLING DIMENSIONS ARE IN MILLIMETERS; INCH DIMENSIONS (IN PARENTHESES) ARE ROUNDED-OFF MILLIMETER EQUIVALENTS FOR REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN

Figure 26. 8-Lead Standard Small Outline Package [SOIC]
Narrow Body
(R-8)
Dimensions shown in millimeters and (inches)

ORDERING GUIDE

Model	Temperature Range	Package Description	Package Option
AD590JH[1]	−55°C to +150°C	TO-52	H-03A
AD590JF[1]	−55°C to +150°C	Flatpack	F-2A
AD590JR	−55°C to +150°C	8-Lead SOIC	SOIC-8
AD590KH[1]	−55°C to +150°C	TO-52	H-03A
AD590KF[1]	−55°C to +150°C	Flatpack	F-2A
AD590KR	−55°C to +150°C	8-Lead SOIC	SOIC-8
AD590LH[1]	−55°C to +150°C	TO-52	H-03A
AD590LF[1]	−55°C to +150°C	Flatpack	F-2A
AD590MH[1]	−55°C to +150°C	TO-52	H-03A
AD590MF[1]	−55°C to +150°C	Flatpack	F-2A
AD590JR-REEL	−55°C to +150°C	8-Lead SOIC	SOIC-8
AD590KR-REEL	−55°C to +150°C	8-Lead SOIC	SOIC-8
AD590JCHIPS	−55°C to +150°C	TO-52	H-03A

[1]Available in 883B; consult factory for data sheet.

Voltage Output Temperature Sensor with Signal Conditioning

AD22100

FEATURES

200°C temperature span
Accuracy better than ±2% of full scale
Linearity better than ±1% of full scale
Temperature coefficient of 22.5 mV/°C
Output proportional to temperature × V+
Single-supply operation
Reverse voltage protection
Minimal self-heating
High level, low impedance output

APPLICATIONS

HVAC systems
System temperature compensation
Board level temperature sensing
Electronic thermostats

MARKETS

Industrial process control
Instrumentation
Automotive

GENERAL DESCRIPTION

The AD22100[1] is a monolithic temperature sensor with on-chip signal conditioning. It can be operated over the temperature range −50°C to +150°C, making it ideal for use in numerous HVAC, instrumentation, and automotive applications.

The signal conditioning eliminates the need for any trimming, buffering, or linearization circuitry, greatly simplifying the system design and reducing the overall system cost.

The output voltage is proportional to the temperature x the supply voltage (ratiometric). The output swings from 0.25 V at −50°C to +4.75 V at +150°C using a single +5.0 V supply.

Due to its ratiometric nature, the AD22100 offers a cost-effective solution when interfacing to an analog-to-digital converter. This is accomplished by using the ADC's +5 V power supply as a reference to both the ADC and the AD22100 eliminating the need for and cost of a precision reference (see Figure 2).

FUNCTIONAL BLOCK DIAGRAM

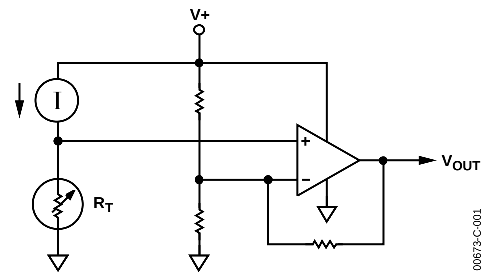


Figure 1.

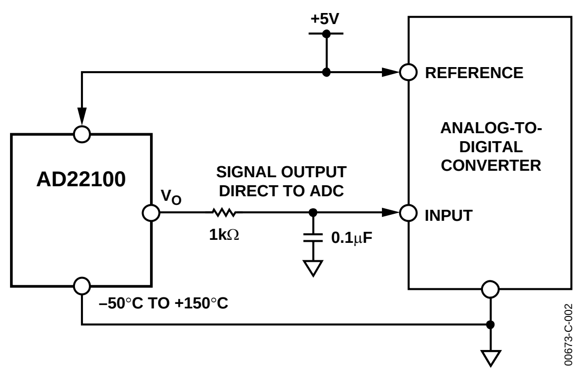


Figure 2. Application Circuit

[1] Protected by U.S. Patent No. 5,030,849 and 5,243,319.

Rev. D

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Fax: 781.326.8703

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12/94—Data Sheet Changed from Rev. A to Rev. B

SPECIFICATIONS

T_A = 25°C and V+ = 4 V to 6.5 V, unless otherwise noted.

Table 1.

Parameter	AD22100K Min	AD22100K Typ	AD22100K Max	AD22100A Min	AD22100A Typ	AD22100A Max	AD22100S Min	AD22100S Typ	AD22100S Max	Unit
TRANSFER FUNCTION	V_{OUT} = (V+/5 V) × [1.375 V +(22.5 mV/°C) × T_A]									V
TEMPERATURE COEFFICIENT	(V+/5 V) × 22.5									mV/°C
TOTAL ERROR										
Initial Error										
T_A = 25°C		±0.5	±2.0		±1.0	±2.0		±1.0	±2.0	°C
Error Overtemperature										
$T_A = T_{MIN}$		±0.75	±2.0		±2.0	±3.7		±3.0	±4.0	°C
$T_A = T_{MAX}$		±0.75	±2.0		±2.0	±3.0		±3.0	±4.0	°C
Nonlinearity										
$T_A = T_{MAX}$ to T_{MIN}			0.5			0.5			1.0	% FS[1]
OUTPUT CHARACTERISTICS										
Nominal Output Voltage										
V+ = 5.0 V, T_A = 0°C		1.375								V
V+ = 5.0 V, T_A = +100°C		3.625								V
V+ = 5.0 V, T_A = −40°C					0.475					V
V+ = 5.0 V, T_A = +85°C					3.288					V
V+ = 5.0 V, T_A = −50°C								0.250		V
V+ = 5.0 V, T_A = +150°C								4.750		V
POWER SUPPLY										
Operating Voltage	4.0	5.0	6.5	4.0	5.0	6.5	4.0	5.0	6.5	V
Quiescent Current		500	650		500	650		500	650	μA
TEMPERATURE RANGE										
Guaranteed Temperature Range	0		+100	−40		+85	−50		+150	°C
Operating Temperature Range	−50		+150	−50		+150	−50		+150	°C
PACKAGE		TO-92 SOIC			TO-92 SOIC			TO-92 SOIC		

[1] FS (full scale) is defined as the operating temperature range −50°C to +150°C. The listed maximum specification limit applies to the guaranteed temperature range. For example, the AD22100K has a nonlinearity of (0.5%) × (200°C) = 1°C over the guaranteed temperature range of 0°C to +100°C.

CHIP SPECIFICATIONS

T_A = 25°C and V+ = 5.0 V, unless otherwise noted.

Table 2.

Paramater	Min	Typ	Max	Unit
TRANSFER FUNCTION	V_{OUT} = (V+/5 V) × [1.375 V +(22.5 mV/°C) × T_A]			V
TEMPERATURE COEFFICIENT	(V+/5 V) × 22.5			mV/°C
OUTPUT CHARACTERISTICS				
Error				
T_A = 25°C		±0.5	±2.0	°C
Nominal Output Voltage				
T_A = 25°C		1.938		V
POWER SUPPLY				
Operating Voltage	4.0	5.0	6.5	V
Quiescent Current		500	650	μA
TEMPERATURE RANGE				
Guaranteed Temperature Range		+25		°C
Operating Temperature Range	−50		+150	°C

ABSOLUTE MAXIMUM RATINGS

Table 3.

Parameter	Rating
Supply Voltage	10 V
Reversed Continuous Supply Voltage	−10 V
Operating Temperature	−50°C to +150°C
Storage Temperature	−65°C to +160°C
Output Short Circuit to V+ or Ground	Indefinite
Lead Temperature Range (Soldering 10 sec)	300°C
Junction Temperature	150°C

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

ESD 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 this product 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.

PIN CONFIGURATIONS AND FUNCTION DESCRIPTIONS

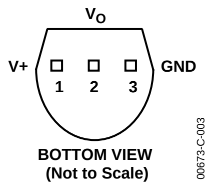

Figure 3. 3-Lead TO-92

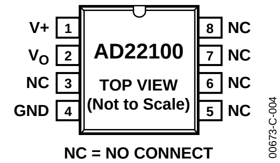

Figure 4. 8-Lead SOIC

Table 4. 3-Lead TO-92 Pin Function Descriptions

Pin No.	Mnemonic	Description
1	V+	Power Supply Input.
2	V_O	Device Output.
3	GND	Ground Pin Must Be Connected to 0 V.

Table 5. 8-Lead SOIC Pin Function Descriptions

Pin No.	Mnemonic	Description
1	V+	Power Supply Input.
2	V_O	Device Output.
3	NC	No Connect.
4	GND	Ground Pin Must Be Connected to 0 V.
5	NC	No Connect.
6	NC	No Connect.
7	NC	No Connect.
8	NC	No Connect.

TYPICAL PERFORMANCE CHARACTERISTICS

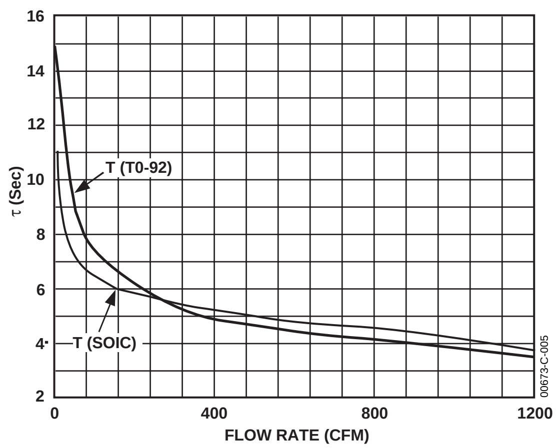

Figure 5. Thermal Response vs. Flow Rate

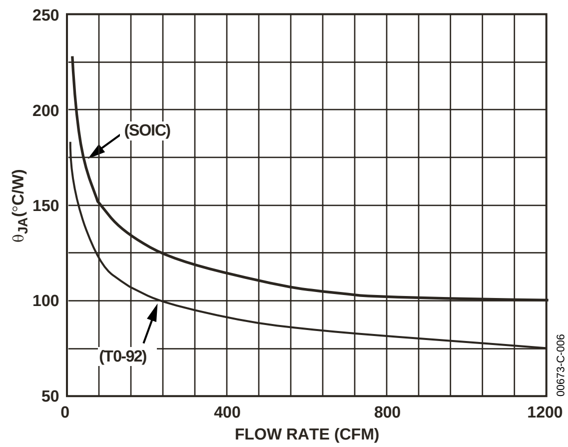

Figure 6. Thermal Resistance vs. Flow Rate

THEORY OF OPERATION

The AD22100 is a ratiometric temperature sensor IC whose output voltage is proportional to its power supply voltage. The heart of the sensor is a proprietary temperature-dependent resistor, similar to an RTD, which is built into the IC. Figure 7 shows a functional block diagram of the AD22100.

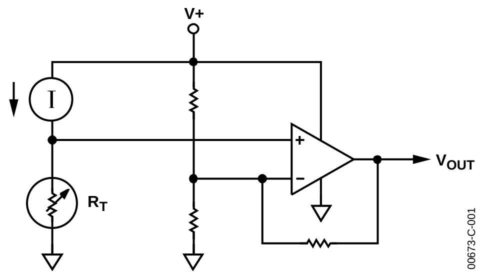

Figure 7. Simplified Block Diagram

The temperature-dependent resistor, labeled R_T, exhibits a change in resistance that is nearly linearly proportional to temperature. This resistor is excited with a current source that is proportional to the power supply voltage. The resulting voltage across R_T is therefore both supply voltage proportional and linearly varying with temperature. The remainder of the AD22100 consists of an op amp signal conditioning block that takes the voltage across R_T and applies the proper gain and offset to achieve the following output voltage function:

$$V_{OUT} = (V+/5\ \text{V}) \times (1.375\ \text{V} + 22.5\ \text{mV/°C} \times T_A)$$

ABSOLUTE ACCURACY AND NONLINEARITY SPECIFICATIONS

Figure 8 graphically depicts the guaranteed limits of accuracy for the AD22100 and shows the performance of a typical part. As the output is very linear, the major sources of error are offset, for instance error at room temperature, span error, and deviation from the theoretical 22.5 mV/°C. Demanding applications can achieve improved performance by calibrating these offset and gain errors so that only the residual nonlinearity remains as a significant source of error.

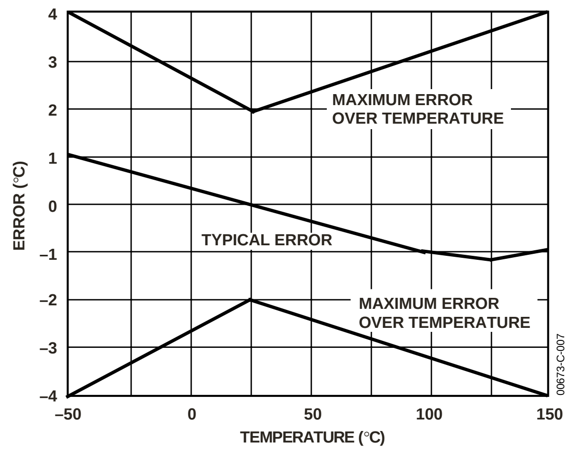

Figure 8. Typical AD22100 Performance

OUTPUT STAGE CONSIDERATIONS

As previously stated, the AD22100 is a voltage output device. A basic understanding of the nature of its output stage is useful for proper application. Note that at the nominal supply voltage of 5.0 V, the output voltage extends from 0.25 V at −50°C to +4.75 V at +150°C. Furthermore, the AD22100 output pin is capable of withstanding an indefinite short circuit to either ground or the power supply. These characteristics are provided by the output stage structure shown in Figure 9.

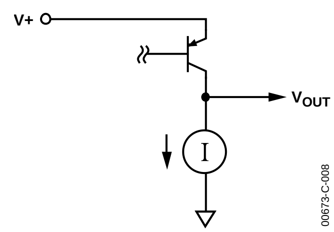

Figure 9. Output Stage Structure

The active portion of the output stage is a PNP transistor, with its emitter connected to the V+ supply and its collector connected to the output node. This PNP transistor sources the required amount of output current. A limited pull-down capability is provided by a fixed current sink of about −80 μA, with the term fixed referring to a current sink that is fairly insensitive to either supply voltage or output loading conditions. The current sink capability is a function of temperature, increasing its pull-down capability at lower temperatures.

Due to its limited current sinking ability, the AD22100 is incapable of driving loads to the V+ power supply and is instead intended to drive grounded loads. A typical value for short-circuit current limit is 7 mA, so devices can reliably source 1 mA or 2 mA. However, for best output voltage accuracy and minimal internal self-heating, output current should be kept below 1 mA. Loads connected to the V+ power supply should be avoided as the current sinking capability of the AD22100 is fairly limited. These considerations are typically not a problem when driving a microcontroller analog-to-digital converter input pin (see the Microprocessor A/D Interface Issues section).

RATIOMETRICITY CONSIDERATIONS

The AD22100 will operate with slightly better accuracy than that listed in the data sheet specifications if the power supply is held constant. This is because the AD22100's output voltage varies with both temperature and supply voltage, with some errors. The ideal transfer function describing output voltage is:

$$(V+/5\text{ V}) \times (1.375\text{ V} + 22.5\text{ mV/°C} \times T_A)$$

The ratiometricity error is defined as the percent change away from the ideal transfer function as the power supply voltage changes within the operating range of 4 V to 6.5 V. For the AD22100, this error is typically less than 1%. A movement from the ideal transfer function by 1% at 25°C, with a supply voltage varying from 5.0 V to 5.50 V, results in a 1.94 mV change in output voltage or 0.08°C error. This error term is greater at higher temperatures because the output (and error term) is directly proportional to temperature. At 150°C, the error in output voltage is 4.75 mV or 0.19°C.

For example, with V_S = 5.0 V, and T_A = +25°C, the nominal output of the AD22100 will be 1.9375 V. At V_S = 5.50 V, the nominal output will be 2.1313 V, an increase of 193.75 mV. A proportionality error of 1% is applied to the 193.75 mV, yielding an error term of 1.9375 mV. This error term translates to a variation in output voltage of 2.1293 V to 2.3332 V. A 1.94 mV error at the output is equivalent to about 0.08°C error in accuracy.

If 150°C is substituted for 25°C in the above example, the error term translates to a variation in output voltage of 5.2203 V to 5.2298 V. A 4.75 mV error at the output is equivalent to about 0.19°C error in accuracy.

MOUNTING CONSIDERATIONS

If the AD22100 is thermally attached and properly protected, it can be used in any measuring situation where the maximum range of temperatures encountered is between −50°C and +150°C. Because plastic IC packaging technology is employed, excessive mechanical stress must be avoided when fastening the device with a clamp or screw-on heat tab. Thermally conductive epoxy or glue is recommended for typical mounting conditions. In wet or corrosive environments, an electrically isolated metal or ceramic well should be used to shield the AD22100. Because the part has a voltage output (as opposed to current), it offers modest immunity to leakage errors, such as those caused by condensation at low temperatures.

THERMAL ENVIRONMENT EFFECTS

The thermal environment in which the AD22100 is used determines two performance traits: the effect of self-heating on accuracy and the response time of the sensor to rapid changes in temperature. In the first case, a rise in the IC junction temperature above the ambient temperature is a function of two variables: the power consumption of the AD22100 and the thermal resistance between the chip and the ambient environment θ_{JA}. Self-heating error in °C can be derived by multiplying the power dissipation by θ_{JA}. Because errors of this type can vary widely for surroundings with different heat-sinking capacities, it is necessary to specify θ_{JA} under several conditions. Table 6 shows how the magnitude of self-heating error varies relative to the environment. A typical part will dissipate about 2.2 mW at room temperature with a 5 V supply and negligible output loading. Table 6 indicates a θ_{JA} of 190°C/W in still air, without a heat sink, yielding a temperature rise of 0.4°C. Thermal rise will be considerably less in either moving air or with direct physical connection to a solid (or liquid) body.

Table 6. Thermal Resistance (TO-92)

Medium	θ_{JA} (°C/W)	*t* (sec)[1]
Aluminum Block	60	2
Moving Air[2]		
Without Heat Sink	75	3.5
Still Air		
Without Heat Sink	190	15

Response of the AD22100 output to abrupt changes in ambient temperature can be modeled by a single time constant *t* exponential function. Figure 10 shows the typical response time plots for a few media of interest.

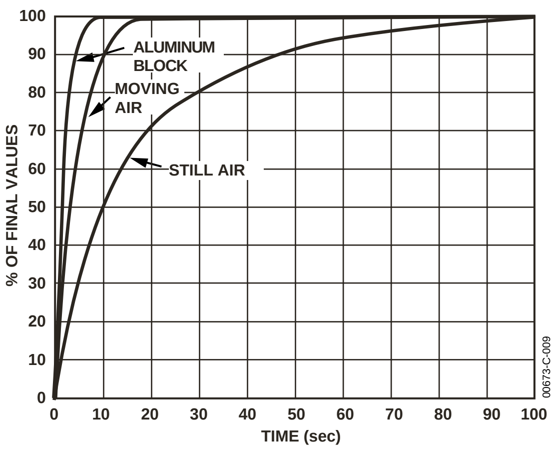

Figure 10. Response Time

The time constant *t* is dependent on θ_{JA} and the thermal capacities of the chip and the package. Table 6 lists the effective *t* (time to reach 63.2% of the final value) for a few different media. Copper printed circuit board connections were neglected in the analysis; however, they will sink or conduct heat directly through the AD22100's solder plated copper leads. When faster response is required, a thermally conductive grease or glue between the AD22100 and the surface temperature being measured should be used.

MICROPROCESSOR A/D INTERFACE ISSUES

The AD22100 is especially well suited to providing a low cost temperature measurement capability for microprocessor/microcontroller based systems. Many inexpensive 8-bit microprocessors now offer an onboard 8-bit ADC capability at a modest cost premium. Total cost of ownership then becomes a function of the voltage reference and analog signal conditioning necessary to mate the analog sensor with the microprocessor ADC. The AD22100 can provide an ideal low cost system by eliminating the need for a precision voltage reference and any additional active components. The ratiometric nature of the AD22100 allows the microprocessor to use the same power supply as its ADC reference. Variations of hundreds of millivolts in the supply voltage have little effect as both the AD22100 and the ADC use the supply as their reference. The nominal AD22100 signal range of 0.25 V to 4.75 V (−50°C to +150°C) makes good use of the input range of a 0 V to 5 V ADC. A single resistor and capacitor are recommended to provide immunity to the high speed charge dump glitches seen at many microprocessor ADC inputs (see Figure 2).

An 8-bit ADC with a reference of 5 V will have a least significant bit (LSB) size of 5 V/256 = 19.5 mV. This corresponds to a nominal resolution of about 0.87°C.

USE WITH A PRECISION REFERENCE AS THE SUPPLY VOLTAGE

While the ratiometric nature of the AD22100 allows for system operation without a precision voltage reference, it can still be used in such systems. Overall system requirements involving other sensors or signal inputs may dictate the need for a fixed precision ADC reference. The AD22100 can be converted to absolute voltage operation by using a precision reference as the supply voltage. For example, a 5.00 V reference can be used to power the AD22100 directly. Supply current will typically be 500 µA, which is usually within the output capability of the reference. Using a large number of AD22100s may require an additional op amp buffer, as would scaling down a 10.00 V reference that might be found in instrumentation ADCs typically operating from ±15 V supplies.

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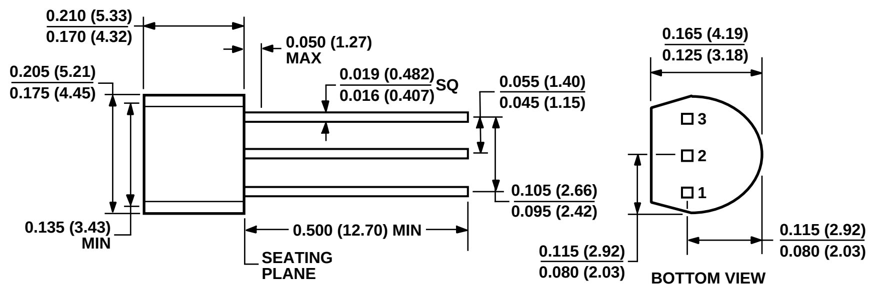
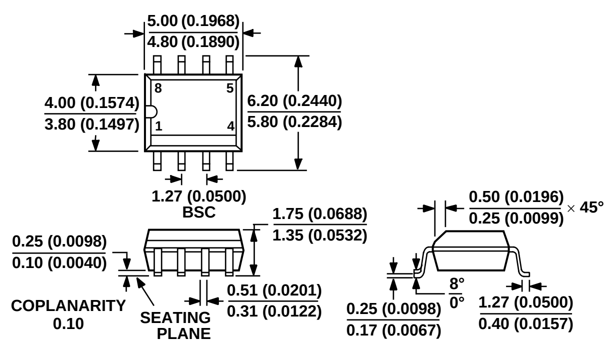
[1] The time constant *t* is defined as the time to reach 63.2% of the final temperature change.
[2] 1200 CFM.

OUTLINE DIMENSIONS



COMPLIANT TO JEDEC STANDARDS TO-226AA
CONTROLLING DIMENSIONS ARE IN INCHES; MILLIMETER DIMENSIONS (IN PARENTHESES) ARE ROUNDED-OFF EQUIVALENTS FOR REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN

Figure 11. 3-Pin Plastic Header Package [TO-92]
(T-3)
Dimensions shown in inches and millimeters

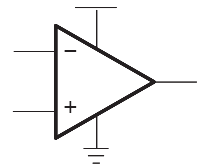


COMPLIANT TO JEDEC STANDARDS MS-012AA
CONTROLLING DIMENSIONS ARE IN MILLIMETERS; INCH DIMENSIONS (IN PARENTHESES) ARE ROUNDED-OFF MILLIMETER EQUIVALENTS FOR REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN

Figure 12. 8-Lead Standard Small Outline Package [SOIC]
(R-8)
Dimensions shown in inches and millimeters

- **Rail-To-Rail Input/Output**
- **Wide Bandwidth . . . 3 MHz**
- **High Slew Rate . . . 2.4 V/μs**
- **Supply Voltage Range . . . 2.7 V to 16 V**
- **Supply Current . . . 550 μA/Channel**
- **Low Power Shutdown Mode**
  $I_{DD(SHDN)}$ . . . 25 μA/Channel
- **Input Noise Voltage . . . 39 nV/√Hz**
- **Input Bias Current . . . 1 pA**
- **Specified Temperature Range**
  −40°C to 125°C . . . Industrial Grade
- **Ultrasmall Packaging**
  5 or 6 Pin SOT-23 (TLV2370/1)
  8 or 10 Pin MSOP (TLV2372/3)

Operational Amplifier



description

The TLV237x single supply operational amplifiers provide rail-to-rail input and output capability. The TLV237x takes the minimum operating supply voltage down to 2.7 V over the extended industrial temperature range while adding the rail-to-rail output swing feature. The TLV237x also provides 3-MHz bandwidth from only 550 μA. The maximum recommended supply voltage is 16 V, which allows the devices to be operated from (±8 V supplies down to ±1.35 V) a variety of rechargeable cells.

The CMOS inputs enable use in high-impedance sensor interfaces, with the lower voltage operation making an ideal alternative for the TLC227x in battery-powered applications. The rail-to-rail input stage further increases its versatility. The TLV237x is the seventh member of a rapidly growing number of RRIO products available from TI, and it is the first to allow operation up to 16-V rails with good ac performance.

All members are available in PDIP and SOIC with the singles in the small SOT-23 package, duals in the MSOP, and quads in the TSSOP package.

The 2.7-V operation makes the TLV237x compatible with Li-Ion powered systems and the operating supply voltage range of many micro-power microcontrollers available today including TI's MSP430.

SELECTION OF SIGNAL AMPLIFIER PRODUCTS†

DEVICE	V_{DD} (V)	V_{IO} (μV)	Iq/Ch (μA)	I_{IB} (pA)	GBW (MHz)	SR (V/μs)	SHUTDOWN	RAIL-TO-RAIL	SINGLES/DUALS/QUADS
TLV237x	2.7−16	500	550	1	3	2.4	Yes	I/O	S/D/Q
TLC227x	4−16	300	1100	1	2.2	3.6	—	O	D/Q
TLV27x	2.7−16	500	550	1	3	2.4	—	O	S/D/Q
TLC27x	3−16	1100	675	1	1.7	3.6	—	—	S/D/Q
TLV246x	2.7−6	150	550	1300	6.4	1.6	Yes	I/O	S/D/Q
TLV247x	2.7−6	250	600	2	2.8	1.5	Yes	I/O	S/D/Q
TLV244x	2.7−10	300	725	1	1.8	1.4	—	O	D/Q

† Typical values measured at 5 V, 25°C

FAMILY PACKAGE TABLE(1)

DEVICE	NUMBER OF CHANNELS	PACKAGE TYPES					SHUTDOWN	UNIVERSAL EVM BOARD
		PDIP	SOIC	SOT-23	TSSOP	MSOP		
TLV2370	1	8	8	6	—	—	Yes	Refer to the EVM Selection Guide (Lit# SLOU060)
TLV2371	1	8	8	5	—	—	—	
TLV2372	2	8	8	—	—	8	—	
TLV2373	2	14	14	—	—	10	Yes	
TLV2374	4	14	14	—	14	—	—	
TLV2375	4	16	16	—	16	—	Yes	

TLV2370 and TLV2371 AVAILABLE OPTIONS(1)

T_A	V_{IO}MAX AT 25°C	PACKAGED DEVICES			
		SMALL OUTLINE (D)†	SOT-23		PLASTIC DIP (P)
			(DBV)‡	SYMBOL	
−40°C to 125°C	4.5 mV	TLV2370ID TLV2371ID	TLV2370IDBV TLV2371IDBV	VBFI VBGI	TLV2370IP TLV2371IP

† This package is available taped and reeled. To order this packaging option, add an **R** suffix to the part number (e.g., TLV2370IDR).
‡ This package is only available taped and reeled. For standard quantities (3,000 pieces per reel), add an **R** suffix (e.g., TLV2370IDBVR). For smaller quantities (250 pieces per mini-reel), add a **T** suffix to the part number (e.g., TLV2370IDBVT).

TLV2372 AND TLV2373 AVAILABLE OPTIONS(1)

T_A	V_{IO}MAX AT 25°C	PACKAGED DEVICES						
		SMALL OUTLINE (D)§	MSOP				PLASTIC DIP (N)	PLASTIC DIP (P)
			(DGK)§	SYMBOL	(DGS)§	SYMBOL		
−40°C to 125°C	4.5 mV	TLV2372ID TLV2373ID	TLV2372IDGK —	APG —	— TLV2373IDGS	— API	— TLV2373IN	TLV2372IP —

§ This package is available taped and reeled. To order this packaging option, add an **R** suffix to the part number (e.g., TLV2372IDR).

TLV2374 and TLV2375 AVAILABLE OPTIONS(1)

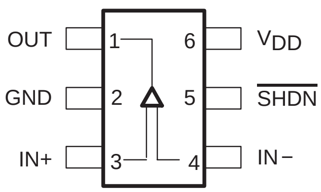
T_A	V_{IO}MAX AT 25°C	PACKAGED DEVICES		
		SMALL OUTLINE (D)¶	PLASTIC DIP (N)	TSSOP (PW)¶
−40°C to 125°C	4.5 mV	TLV2374ID TLV2375ID	TLV2374IN TLV2375IN	TLV2374IPW TLV2375IPW

¶ This package is available taped and reeled. To order this packaging option, add an **R** suffix to the part number (e.g., TLV2374IDR).

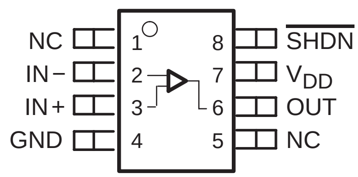
1. For the most current package and ordering information, see the Package Option Addendum at the end of this document, or see the TI website at www.ti.com.

TLV237x PACKAGE PINOUTS(1)

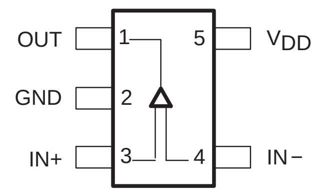
TLV2370
DBV PACKAGE
(TOP VIEW)



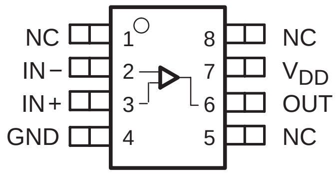
TLV2370
D OR P PACKAGE
(TOP VIEW)



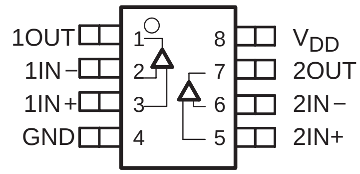
TLV2371
DBV PACKAGE
(TOP VIEW)



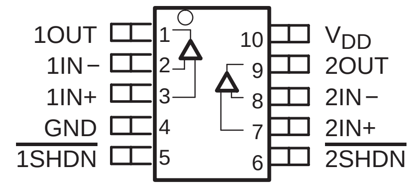
TLV2371
D OR P PACKAGE
(TOP VIEW)



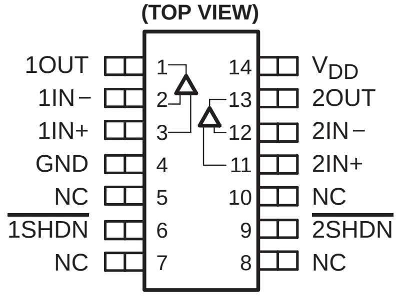
TLV2372
D, DGK, OR P PACKAGE
(TOP VIEW)



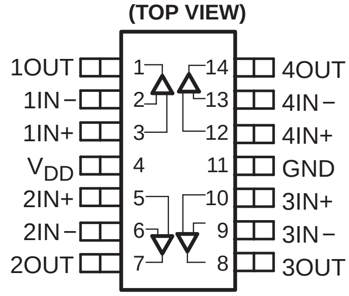
TLV2373
DGS PACKAGE
(TOP VIEW)



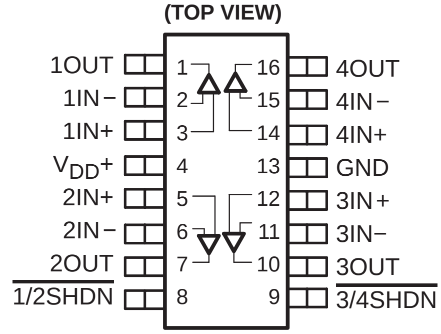
TLV2373
D OR N PACKAGE
(TOP VIEW)



TLV2374
D, N, OR PW PACKAGE
(TOP VIEW)

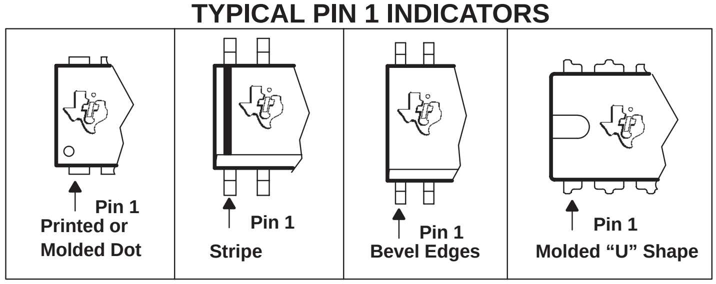


TLV2375
D, N, OR PW PACKAGE
(TOP VIEW)



NC − No internal connection

TYPICAL PIN 1 INDICATORS



NOTE: (1) If there is not a Pin 1 indicator, turn device to enable reading the symbol from the left to right. Pin 1 is at the lower left corner of the device.

absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†

Supply voltage, V_{DD} (see Note 1) .... 16.5 V
Differential input voltage, V_{ID} .... $\pm V_{DD}$
Input voltage range, V_I (see Note 1) .... −0.2 V to V_{DD} + 0.2 V
Input current range, I_I .... ±10 mA
Output current range, I_O .... ±100 mA
Continuous total power dissipation .... See Dissipation Rating Table
Operating free-air temperature range, T_A: I-suffix .... −40°C to 125°C
Maximum junction temperature, T_J .... 150°C
Storage temperature range, T_{stg} .... −65°C to 150°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds .... 260°C

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTE: All voltage values, except differential voltages, are with respect to GND.

DISSIPATION RATING TABLE

PACKAGE	θ_{JC} (°C/W)	θ_{JA} (°C/W)	$T_A \le 25°C$ POWER RATING
D (8)	38.3	176	710 mW
D (14)	26.9	122.3	1022 mW
D (16)	25.7	114.7	1090 mW
DBV (5)	55	324.1	385 mW
DBV (6)	55	294.3	425 mW
DGK (8)	54.23	259.96	481 mW
DGS (10)	54.1	257.71	485 mW
N (14, 16)	32	78	1600 mW
P (8)	41	104	1200 mW
PW (14)	29.3	173.6	720 mW
PW (16)	28.7	161.4	774 mW

recommended operating conditions

		MIN	MAX	UNIT
Supply voltage, V_{DD}	Single supply	2.7	16	V
	Split supply	±1.35	±8	
Common-mode input voltage range, V_{ICR}		0	V_{DD}	V
Operating free-air temperature, T_A	I-suffix	−40	125	°C
Turnon voltage level, $V_{(ON)}$, relative to GND pin voltage			2	V
Turnoff voltage level, $V_{(OFF)}$, relative to GND pin voltage		0.8		V

electrical characteristics at specified free-air temperature, V_{DD} = 2.7 V, 5 V, and 15 V (unless otherwise noted)

dc performance

PARAMETER		TEST CONDITIONS		T_A	MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	$V_{IC} = V_{DD}/2$, $V_O = V_{DD}/2$, $R_S = 50\ \Omega$		25°C		2	4.5	mV
				Full range			6	
α_{VIO}	Offset voltage drift			25°C		2		µV/°C
CMRR	Common-mode rejection ratio	V_{IC} = 0 to V_{DD}, $R_S = 50\ \Omega$	V_{DD} = 2.7 V	25°C	50	68		dB
				Full range	49			
		V_{IC} = 0 to V_{DD}−1.35V, $R_S = 50\ \Omega$		25°C	56	70		
				Full range	54			
		V_{IC} = 0 to V_{DD}, $R_S = 50\ \Omega$,	V_{DD} = 5 V	25°C	55	72		
				Full range	54			
		V_{IC} = 0 to V_{DD}−1.35V, $R_S = 50\ \Omega$,		25°C	67	80		
				Full range	64			
		V_{IC} = 0 to V_{DD}, $R_S = 50\ \Omega$,	V_{DD} = 15 V	25°C	64	82		
				Full range	63			
		V_{IC} = 0 to V_{DD}−1.35V, $R_S = 50\ \Omega$,		25°C	67	84		
				Full range	66			
A_{VD}	Large-signal differential voltage amplification	$V_{O(PP)} = V_{DD}/2$, $R_L = 10\ k\Omega$	V_{DD} = 2.7 V	25°C	98	106		dB
				Full range	76			
			V_{DD} = 5 V	25°C	100	110		
				Full range	86			
			V_{DD} = 15 V	25°C	81	83		
				Full range	79			

input characteristics

PARAMETER		TEST CONDITIONS	T_A	MIN	TYP	MAX	UNIT
I_{IO}	Input offset current	V_{DD} = 15 V, $V_{IC} = V_{DD}/2$, $V_O = V_{DD}/2$	25°C		1	60	pA
			70°C			100	
			125°C			1000	
I_{IB}	Input bias current		25°C		1	60	pA
			70°C			100	
			125°C			1000	
$r_{i(d)}$	Differential input resistance		25°C		1000		GΩ
C_{IC}	Common-mode input capacitance	f = 21 kHz	25°C		8		pF

electrical characteristics at specified free-air temperature, V_{DD} = 2.7 V, 5 V, and 15 V (unless otherwise noted) (continued)

output characteristics

PARAMETER		TEST CONDITIONS		T_A	MIN	TYP	MAX	UNIT
V_{OH}	High-level output voltage	$V_{IC} = V_{DD}/2$, I_{OH} = −1 mA	V_{DD} = 2.7 V	25°C	2.55	2.58		V
				Full range	2.48			
			V_{DD} = 5 V	25°C	4.9	4.93		
				Full range	4.85			
			V_{DD} = 15 V	25°C	14.92	14.96		
				Full range	14.9			
		$V_{IC} = V_{DD}/2$, I_{OH} = −5 mA	V_{DD} = 2.7 V	25°C	1.9	2		
				Full range	1.6			
			V_{DD} = 5 V	25°C	4.6	4.68		
				Full range	4.5			
			V_{DD} = 15 V	25°C	14.7	14.8		
				Full range	14.6			
V_{OL}	Low-level output voltage	$V_{IC} = V_{DD}/2$, I_{OL} = 1 mA	V_{DD} = 2.7 V	25°C		0.1	0.15	V
				Full range			0.22	
			V_{DD} = 5 V	25°C		0.05	0.1	
				Full range			0.15	
			V_{DD} = 15 V	25°C		0.05	0.08	
				Full range			0.1	
		$V_{IC} = V_{DD}/2$, I_{OL} = 5 mA	V_{DD} = 2.7 V	25°C		0.52	0.7	
				Full range			1.1	
			V_{DD} = 5 V	25°C		0.28	0.4	
				Full range			0.5	
			V_{DD} = 15 V	25°C		0.19	0.3	
				Full range			0.35	
I_O	Output current	V_{DD} = 2.7 V, V_O = 0.5 V from rail	Positive rail	25°C		4		mA
			Negative rail	25°C		5		
		V_{DD} = 5 V, V_O = 0.5 V from rail	Positive rail	25°C		7		
			Negative rail	25°C		8		
		V_{DD} = 15 V, V_O = 0.5 V from rail	Positive rail	25°C		16		
			Negative rail	25°C		15		

power supply

PARAMETER		TEST CONDITIONS		T_A	MIN	TYP	MAX	UNIT
I_{DD}	Supply current (per channel)	$V_O = V_{DD}/2$,	V_{DD} = 2.7 V	25°C		470	560	μA
			V_{DD} = 5 V	25°C		550	660	
			V_{DD} = 15 V	25°C		750	900	
				Full range			1200	
PSRR	Supply voltage rejection ratio ($\Delta V_{DD} / \Delta V_{IO}$)	V_{DD} = 2.7 V to 15 V, $V_{IC} = V_{DD}/2$, No load		25°C	70	80		dB
				Full range	65			

electrical characteristics at specified free-air temperature, V_{DD} = 2.7 V, 5 V, and 15 V (unless otherwise noted) (continued)

dynamic performance

PARAMETER		TEST CONDITIONS		T_A	MIN	TYP	MAX	UNIT
UGBW	Unity gain bandwidth	R_L = 2 kΩ, C_L = 10 pF	V_{DD} = 2.7 V	25°C		2.4		MHz
			V_{DD} = 5 V to 15 V	25°C		3		
SR	Slew rate at unity gain	$V_{O(PP)} = V_{DD}/2$, C_L = 50 pF, R_L = 10 kΩ	V_{DD} = 2.7 V	25°C	1.4	2		V/μs
				Full range	1			
			V_{DD} = 5 V	25°C	1.6	2.4		V/μs
				Full range	1.2			
			V_{DD} = 15 V	25°C	1.9	2.1		V/μs
				Full range	1.4			
ϕ_m	Phase margin	R_L = 2 kΩ,	C_L = 100 pF	25°C		65°		
	Gain margin	R_L = 2 kΩ,	C_L = 10 pF	25°C		18		dB
t_s	Settling time	V_{DD} = 2.7 V, $V_{(STEP)PP}$ = 1 V, A_V = −1, C_L = 10 pF, R_L = 2 kΩ	0.1%	25°C		2.9		μs
		V_{DD} = 5 V, 15 V, $V_{(STEP)PP}$ = 1 V, A_V = −1, C_L = 47 pF, R_L = 2 kΩ	0.1%			2		

noise/distortion performance

PARAMETER		TEST CONDITIONS		T_A	MIN	TYP	MAX	UNIT
THD + N	Total harmonic distortion plus noise	V_{DD} = 2.7 V, $V_{O(PP)} = V_{DD}/2$ V, R_L = 2 kΩ, f = 10 kHz	A_V = 1	25°C		0.02%		
			A_V = 10			0.05%		
			A_V = 100			0.18%		
		V_{DD} = 5 V, 15 V, $V_{O(PP)} = V_{DD}/2$ V, R_L = 2 kΩ, f = 10 kHz	A_V = 1	25°C		0.02%		
			A_V = 10			0.09%		
			A_V = 100			0.5%		
V_n	Equivalent input noise voltage	f = 1 kHz		25°C		39		$nV/\sqrt{Hz}$
		f = 10 kHz				35		
I_n	Equivalent input noise current	f = 1 kHz		25°C		0.6		$fA/\sqrt{Hz}$

shutdown characteristics

PARAMETER		TEST CONDITIONS	T_A	MIN	TYP	MAX	UNIT
$I_{DD(SHDN)}$	Supply current in shutdown mode (TLV2370, TLV2373, TLV2375) (per channel)	V_{DD} = 2.7 V, 5 V, $\overline{SHDN}$ = 0 V	25°C		25	30	μA
			Full range			35	
		V_{DD} = 15 V, $\overline{SHDN}$ = 0 V	25°C		40	45	μA
			Full range			50	
$t_{(on)}$	Amplifier turnon time (see Note 2)	R_L = 2 kΩ	25°C		0.8		μs
$t_{(off)}$	Amplifier turnoff time (see Note 2)		25°C		1		μs

NOTE: Disable time and enable time are defined as the interval between application of the logic signal to the $\overline{SHDN}$ terminal and the point at which the supply current has reached one half of its final value.

TYPICAL CHARACTERISTICS

Table of Graphs

			FIGURE
V_{IO}	Input offset voltage	vs Common-mode input voltage	1, 2, 3
CMRR	Common-mode rejection ratio	vs Frequency	4
	Input bias and offset current	vs Free-air temperature	5
V_{OL}	Low-level output voltage	vs Low-level output current	6, 8, 10
V_{OH}	High-level output voltage	vs High-level output current	7, 9, 11
$V_{O(PP)}$	Peak-to-peak output voltage	vs Frequency	12
I_{DD}	Supply current	vs Supply voltage	13
PSRR	Power supply rejection ratio	vs Frequency	14
A_{VD}	Differential voltage gain & phase	vs Frequency	15
	Gain-bandwidth product	vs Free-air temperature	16
SR	Slew rate	vs Supply voltage	17
		vs Free-air temperature	18
ϕ_m	Phase margin	vs Capacitive load	19
V_n	Equivalent input noise voltage	vs Frequency	20
	Voltage-follower large-signal pulse response		21, 22
	Voltage-follower small-signal pulse response		23
	Inverting large-signal response		24, 25
	Inverting small-signal response		26
	Crosstalk	vs Frequency	27
	Shutdown forward & reverse isolation	vs Frequency	28
$I_{DD(SHDN)}$	Shutdown supply current	vs Supply voltage	29
$I_{DD(SHDN)}$	Shutdown pin leakage current	vs Shutdown pin voltage	30
$I_{DD(SHDN)}$	Shutdown supply current/output voltage	vs Time	31, 32

TYPICAL CHARACTERISTICS

**INPUT OFFSET VOLTAGE
vs
COMMON-MODE INPUT VOLTAGE**

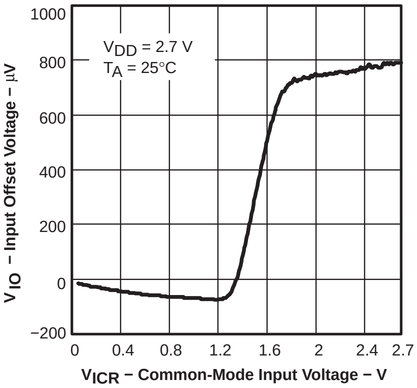


Figure 1

**INPUT OFFSET VOLTAGE
vs
COMMON-MODE INPUT VOLTAGE**

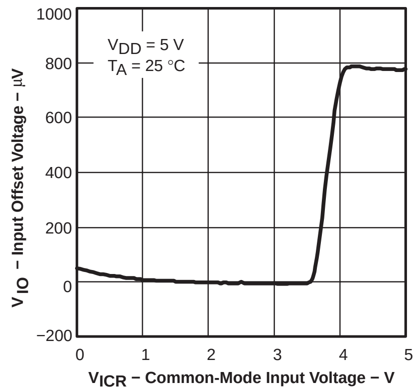


Figure 2

**INPUT OFFSET VOLTAGE
vs
COMMON-MODE INPUT VOLTAGE**

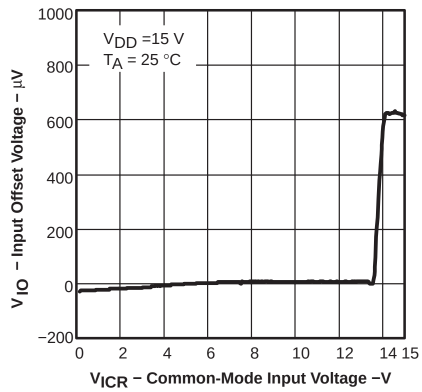


Figure 3

**COMMON-MODE REJECTION RATIO
vs
FREQUENCY**

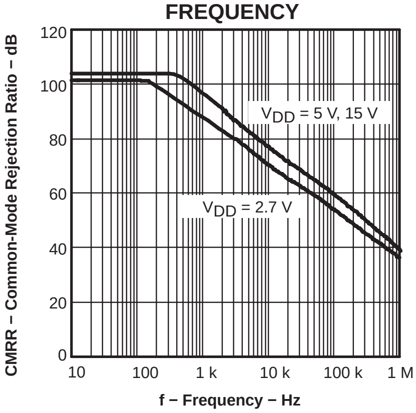


Figure 4

**INPUT BIAS/OFFSET CURRENT
vs
FREE-AIR TEMPERATURE**

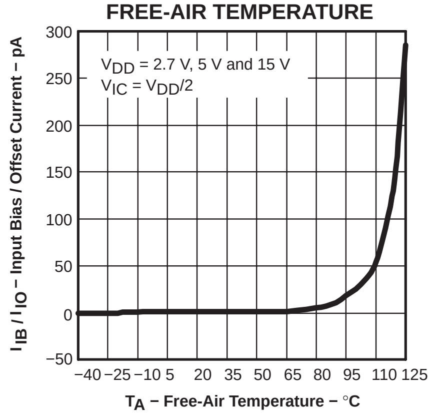


Figure 5

**LOW-LEVEL OUTPUT VOLTAGE
vs
LOW-LEVEL OUTPUT CURRENT**

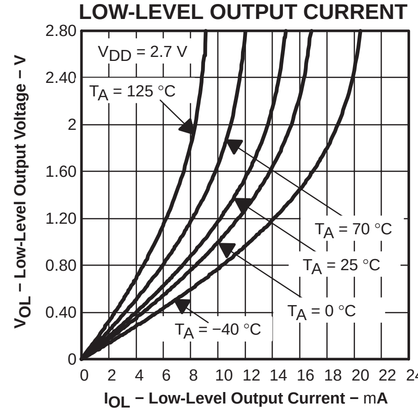


Figure 6

**HIGH-LEVEL OUTPUT VOLTAGE
vs
HIGH-LEVEL OUTPUT CURRENT**

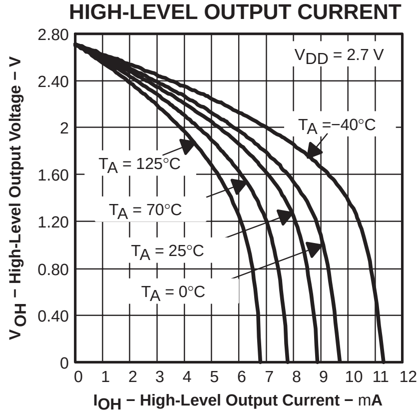


Figure 7

**LOW-LEVEL OUTPUT VOLTAGE
vs
LOW-LEVEL OUTPUT CURRENT**

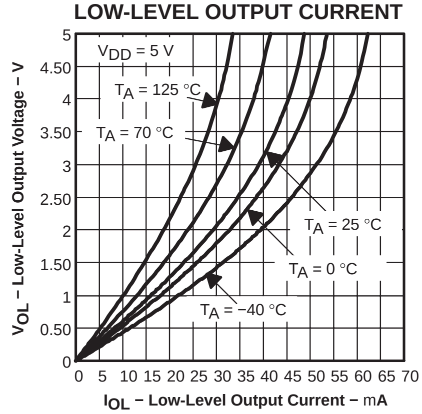


Figure 8

**HIGH-LEVEL OUTPUT VOLTAGE
vs
HIGH-LEVEL OUTPUT CURRENT**

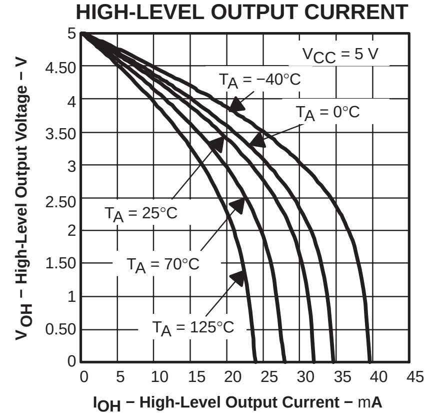


Figure 9

TYPICAL CHARACTERISTICS

LOW-LEVEL OUTPUT VOLTAGE vs LOW-LEVEL OUTPUT CURRENT

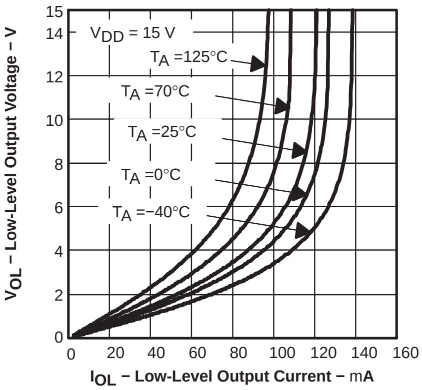


Figure 10

HIGH-LEVEL OUTPUT VOLTAGE vs HIGH-LEVEL OUTPUT CURRENT

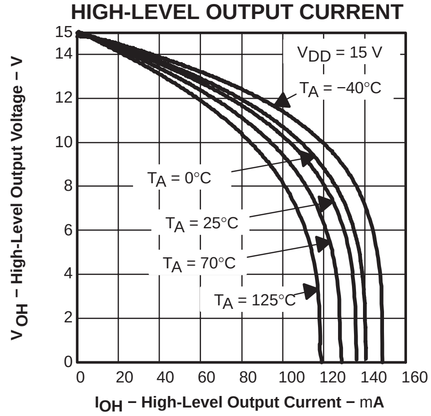


Figure 11

PEAK-TO-PEAK OUTPUT VOLTAGE vs FREQUENCY

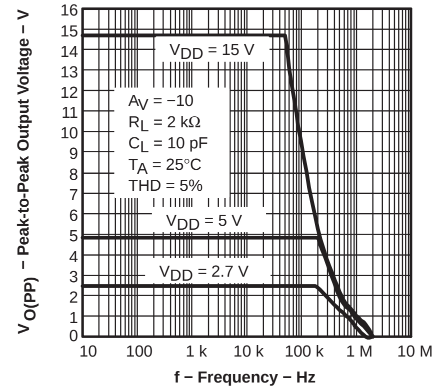


Figure 12

SUPPLY CURRENT vs SUPPLY VOLTAGE

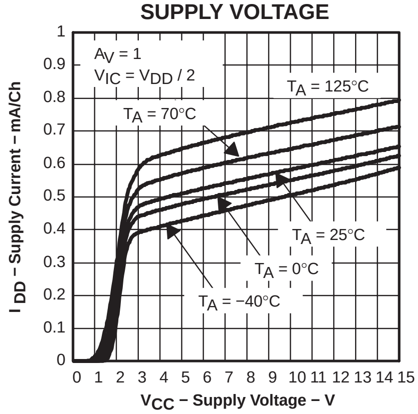


Figure 13

POWER SUPPLY REJECTION RATIO vs FREQUENCY

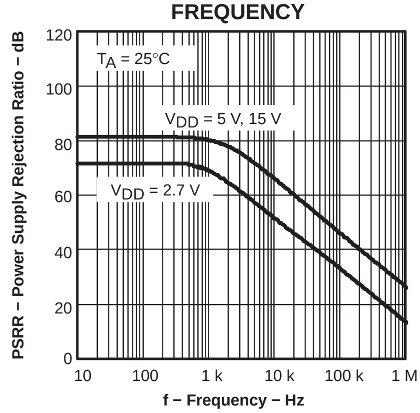


Figure 14

DIFFERENTIAL VOLTAGE GAIN AND PHASE vs FREQUENCY

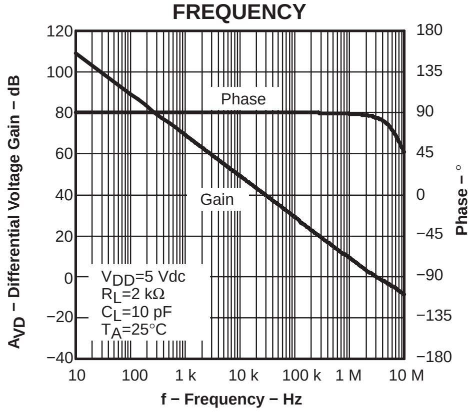


Figure 15

GAIN BANDWIDTH PRODUCT vs FREE-AIR TEMPERATURE

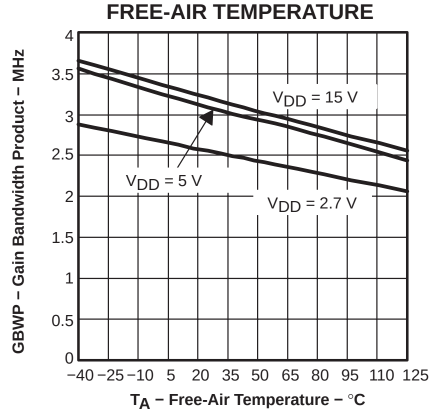


Figure 16

TYPICAL CHARACTERISTICS

SLEW RATE vs SUPPLY VOLTAGE

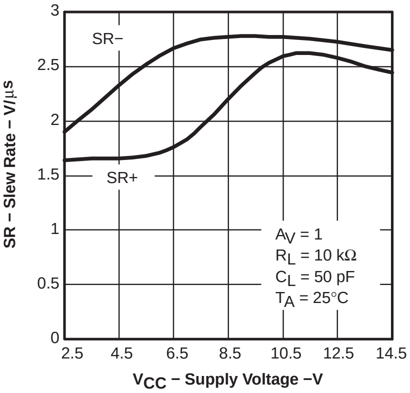


Figure 17

SLEW RATE vs FREE-AIR TEMPERATURE

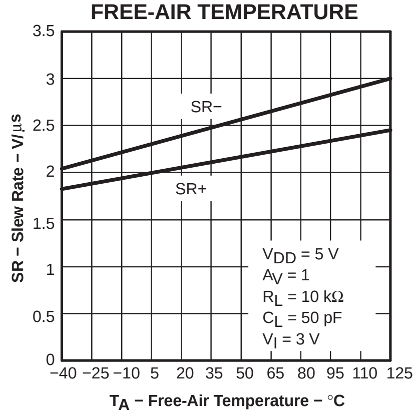


Figure 18

PHASE MARGIN vs CAPACITIVE LOAD

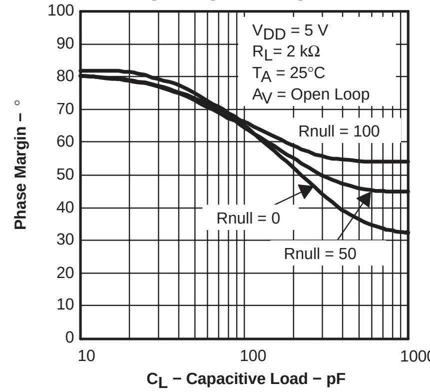


Figure 19

EQUIVALENT INPUT NOISE VOLTAGE vs FREQUENCY

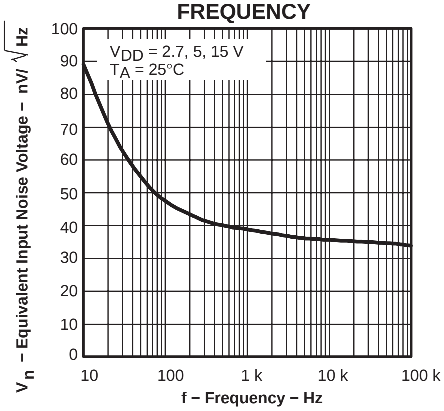


Figure 20

VOLTAGE-FOLLOWER LARGE-SIGNAL PULSE RESPONSE

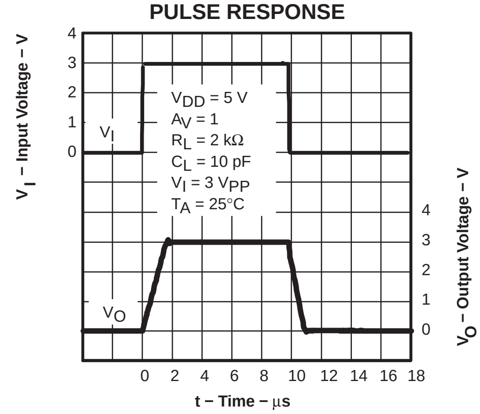


Figure 21

VOLTAGE-FOLLOWER LARGE-SIGNAL PULSE RESPONSE

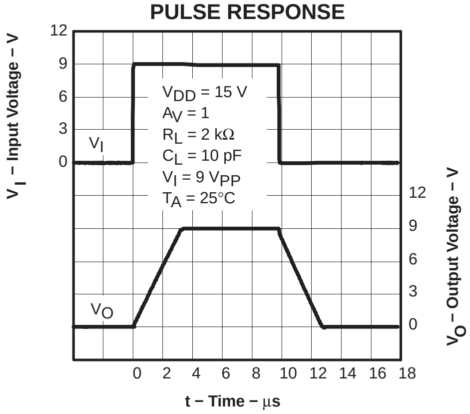


Figure 22

VOLTAGE-FOLLOWER SMALL-SIGNAL PULSE RESPONSE

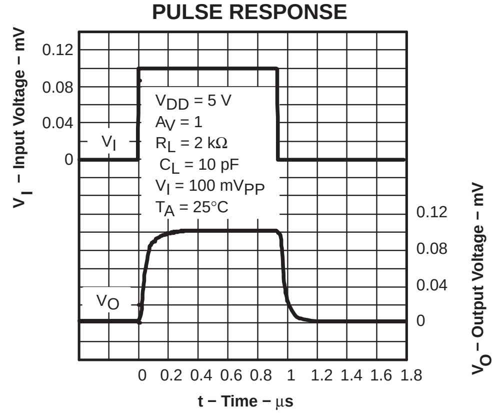


Figure 23

TYPICAL CHARACTERISTICS

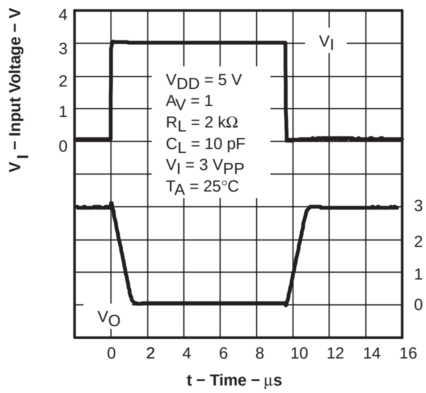


Figure 24

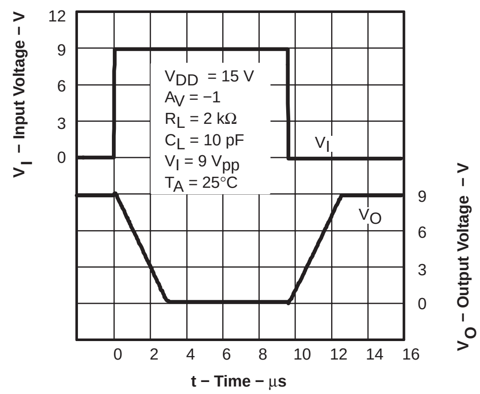


Figure 25

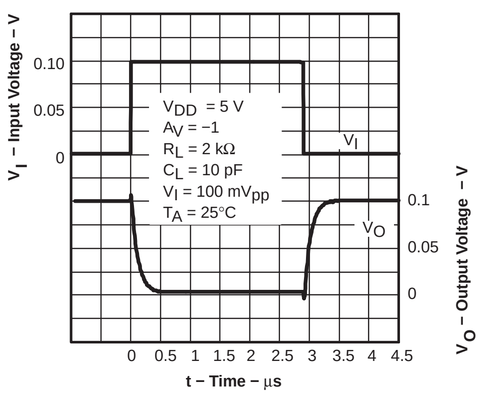


Figure 26

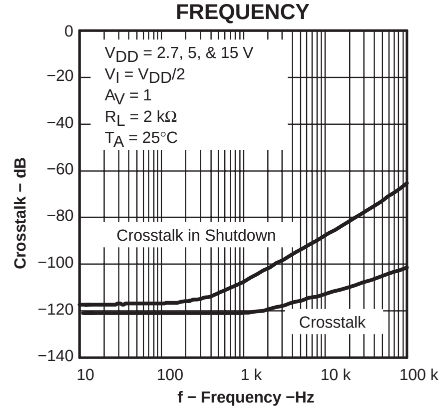


Figure 27

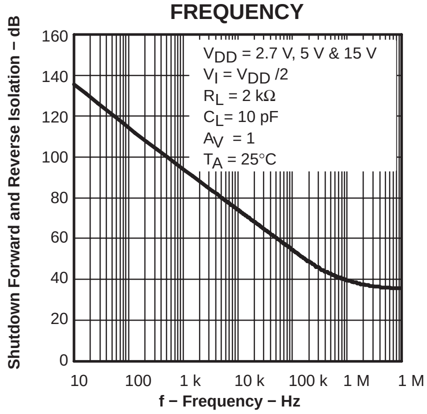


Figure 28

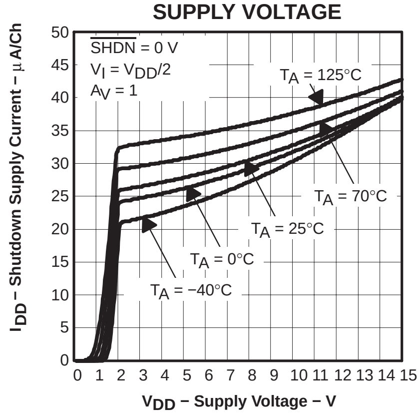


Figure 29

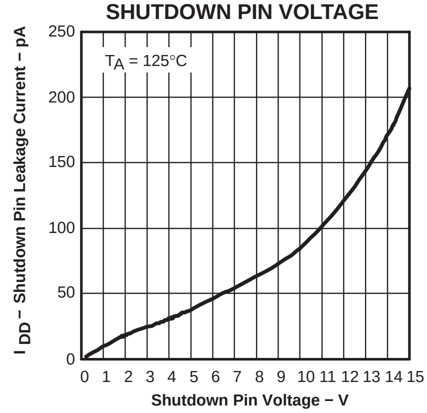


Figure 30

TYPICAL CHARACTERISTICS

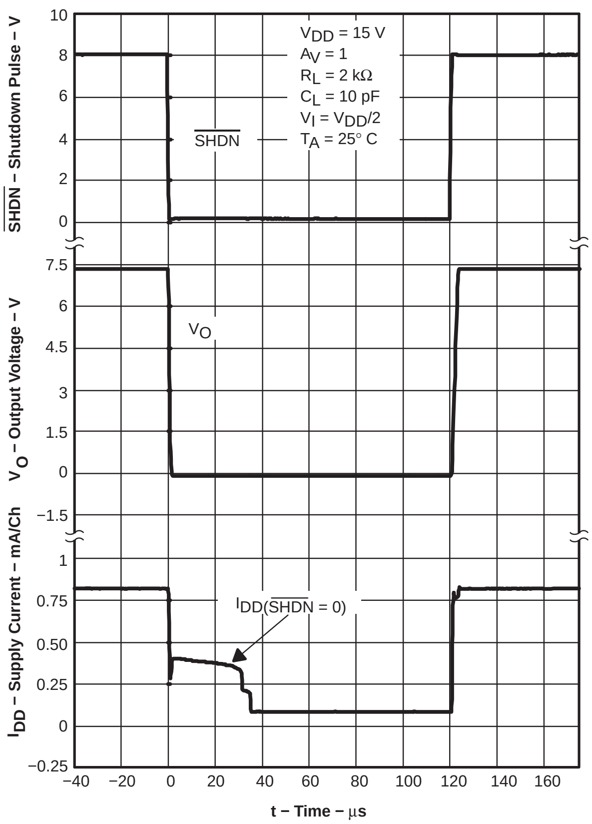


Figure 31

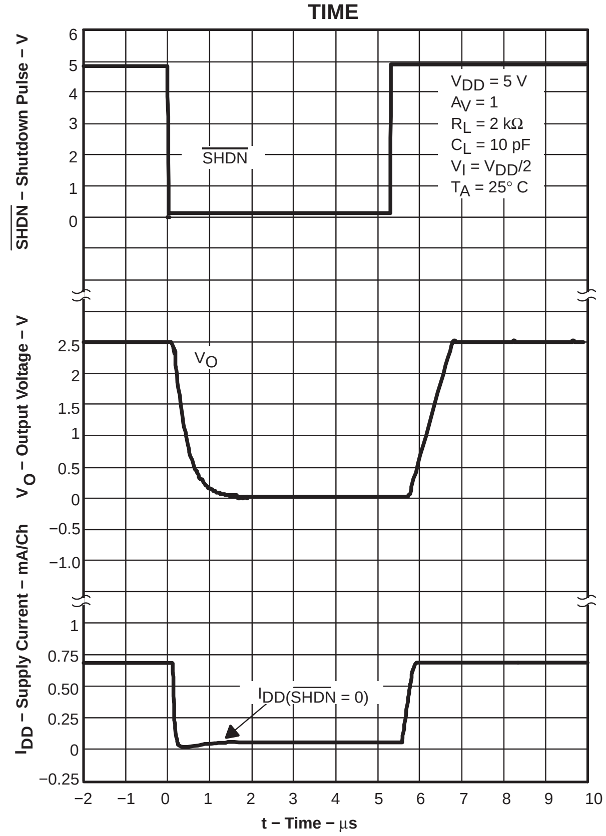


Figure 32

APPLICATION INFORMATION

rail-to-rail input operation

The TLV237x input stage consists of two differential transistor pairs, NMOS and PMOS, that operate together to achieve rail-to-rail input operation. The transition point between these two pairs can be seen in Figure 1, Figure 2, and Figure 3 for a 2.7-V, 5-V, and 15-V supply. As the common-mode input voltage approaches the positive supply rail, the input pair switches from the PMOS differential pair to the NMOS differential pair. This transition occurs approximately 1.35 V from the positive rail and results in a change in offset voltage due to different device characteristics between the NMOS and PMOS pairs. If the input signal to the device is large enough to swing between both rails, this transition results in a reduction in common-mode rejection ratio (CMRR). If the input signal does not swing between both rails, it is best to bias the signal in the region where only one input pair is active. This is the region in Figure 1 through Figure 3 where the offset voltage varies slightly across the input range and optimal CMRR can be achieved. This has the greatest impact when operating from a 2.7-V supply voltage.

driving a capacitive load

When the amplifier is configured in this manner, capacitive loading directly on the output decreases the device's phase margin leading to high frequency ringing or oscillations. Therefore, for capacitive loads of greater than 10 pF, it is recommended that a resistor be placed in series (R_{NULL}) with the output of the amplifier, as shown in Figure 33. A minimum value of 20 Ω should work well for most applications.

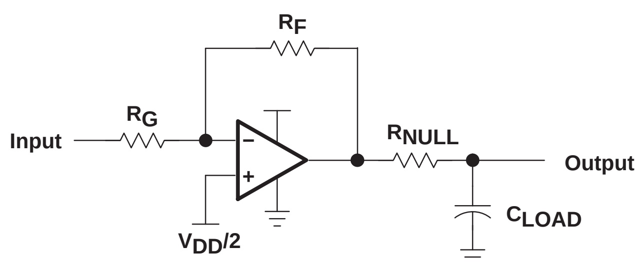
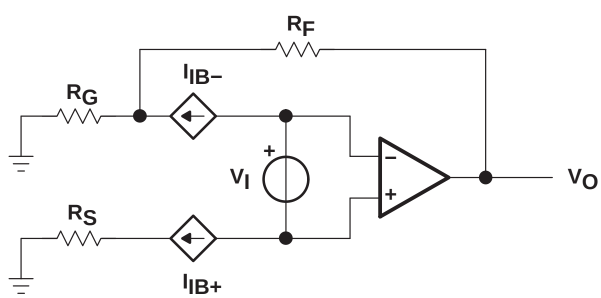


Figure 33. Driving a Capacitive Load

offset voltage

The output offset voltage, (V_{OO}) is the sum of the input offset voltage (V_{IO}) and both input bias currents (I_{IB}) times the corresponding gains. The following schematic and formula can be used to calculate the output offset voltage:



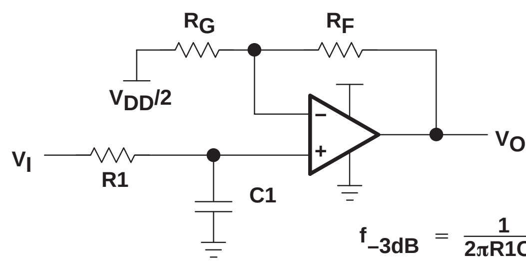
$$V_{OO} = V_{IO}\left(1 + \left(\frac{R_F}{R_G}\right)\right) \pm I_{IB+}\, R_S \left(1 + \left(\frac{R_F}{R_G}\right)\right) \pm I_{IB-}\, R_F$$

Figure 34. Output Offset Voltage Model

APPLICATION INFORMATION

general configurations

When receiving low-level signals, limiting the bandwidth of the incoming signals into the system is often required. The simplest way to accomplish this is to place an RC filter at the noninverting terminal of the amplifier (see Figure 35).

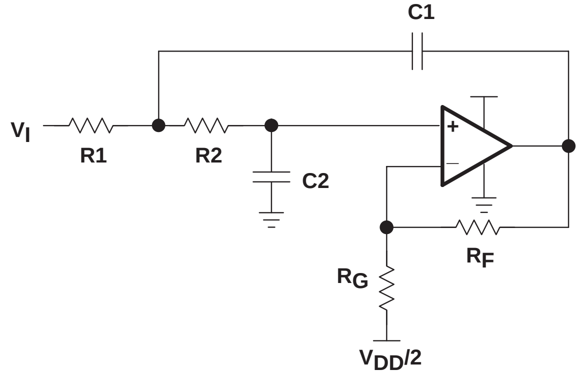


$$f_{-3dB} = \frac{1}{2\pi R1C1}$$

$$\frac{V_O}{V_I} = \left(1 + \frac{R_F}{R_G}\right)\left(\frac{1}{1 + 2\pi fR1C1}\right)$$

Figure 35. Single-Pole Low-Pass Filter

If even more attenuation is needed, a multiple pole filter is required. The Sallen-Key filter can be used for this task. For best results, the amplifier should have a bandwidth that is 8 to 10 times the filter frequency bandwidth. Failure to do this can result in phase shift of the amplifier.



R1 = R2 = R
C1 = C2 = C
Q = Peaking Factor
(Butterworth Q = 0.707)

$$f_{-3dB} = \frac{1}{2\pi RC}$$

$$R_G = \frac{R_F}{\left(2 - \frac{1}{Q}\right)}$$

Figure 36. 2-Pole Low-Pass Sallen-Key Filter

APPLICATION INFORMATION

circuit layout considerations

To achieve the levels of high performance of the TLV237x, follow proper printed-circuit board design techniques. A general set of guidelines is given in the following.

- Ground planes—It is highly recommended that a ground plane be used on the board to provide all components with a low inductive ground connection. However, in the areas of the amplifier inputs and output, the ground plane can be removed to minimize the stray capacitance.
- Proper power supply decoupling—Use a 6.8-μF tantalum capacitor in parallel with a 0.1-μF ceramic capacitor on each supply terminal. It may be possible to share the tantalum among several amplifiers depending on the application, but a 0.1-μF ceramic capacitor should always be used on the supply terminal of every amplifier. In addition, the 0.1-μF capacitor should be placed as close as possible to the supply terminal. As this distance increases, the inductance in the connecting trace makes the capacitor less effective. The designer should strive for distances of less than 0.1 inches between the device power terminals and the ceramic capacitors.
- Sockets—Sockets can be used but are not recommended. The additional lead inductance in the socket pins will often lead to stability problems. Surface-mount packages soldered directly to the printed-circuit board is the best implementation.
- Short trace runs/compact part placements—Optimum high performance is achieved when stray series inductance has been minimized. To realize this, the circuit layout should be made as compact as possible, thereby minimizing the length of all trace runs. Particular attention should be paid to the inverting input of the amplifier. Its length should be kept as short as possible. This helps to minimize stray capacitance at the input of the amplifier.
- Surface-mount passive components—Using surface-mount passive components is recommended for high performance amplifier circuits for several reasons. First, because of the extremely low lead inductance of surface-mount components, the problem with stray series inductance is greatly reduced. Second, the small size of surface-mount components naturally leads to a more compact layout thereby minimizing both stray inductance and capacitance. If leaded components are used, it is recommended that the lead lengths be kept as short as possible.

shutdown function

Three members of the TLV237x family (TLV2370/3/5) have a shutdown terminal for conserving battery life in portable applications. When the shutdown terminal is tied low, the supply current is reduced to 25 μA/channel, the amplifier is disabled, and the outputs are placed in a high impedance mode. To enable the amplifier, the shutdown terminal can either be left floating or pulled high. When the shutdown terminal is left floating, care should be taken to ensure that parasitic leakage current at the shutdown terminal does not inadvertently place the operational amplifier into shutdown.

APPLICATION INFORMATION

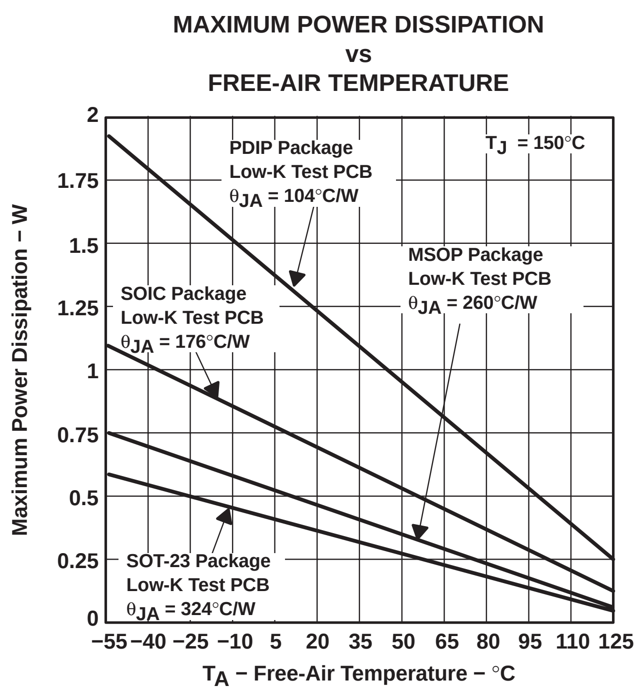
general power dissipation considerations

For a given θ_{JA}, the maximum power dissipation is shown in Figure 37 and is calculated by the following formula:

$$P_D = \left(\frac{T_{MAX} - T_A}{\theta_{JA}}\right)$$

Where:

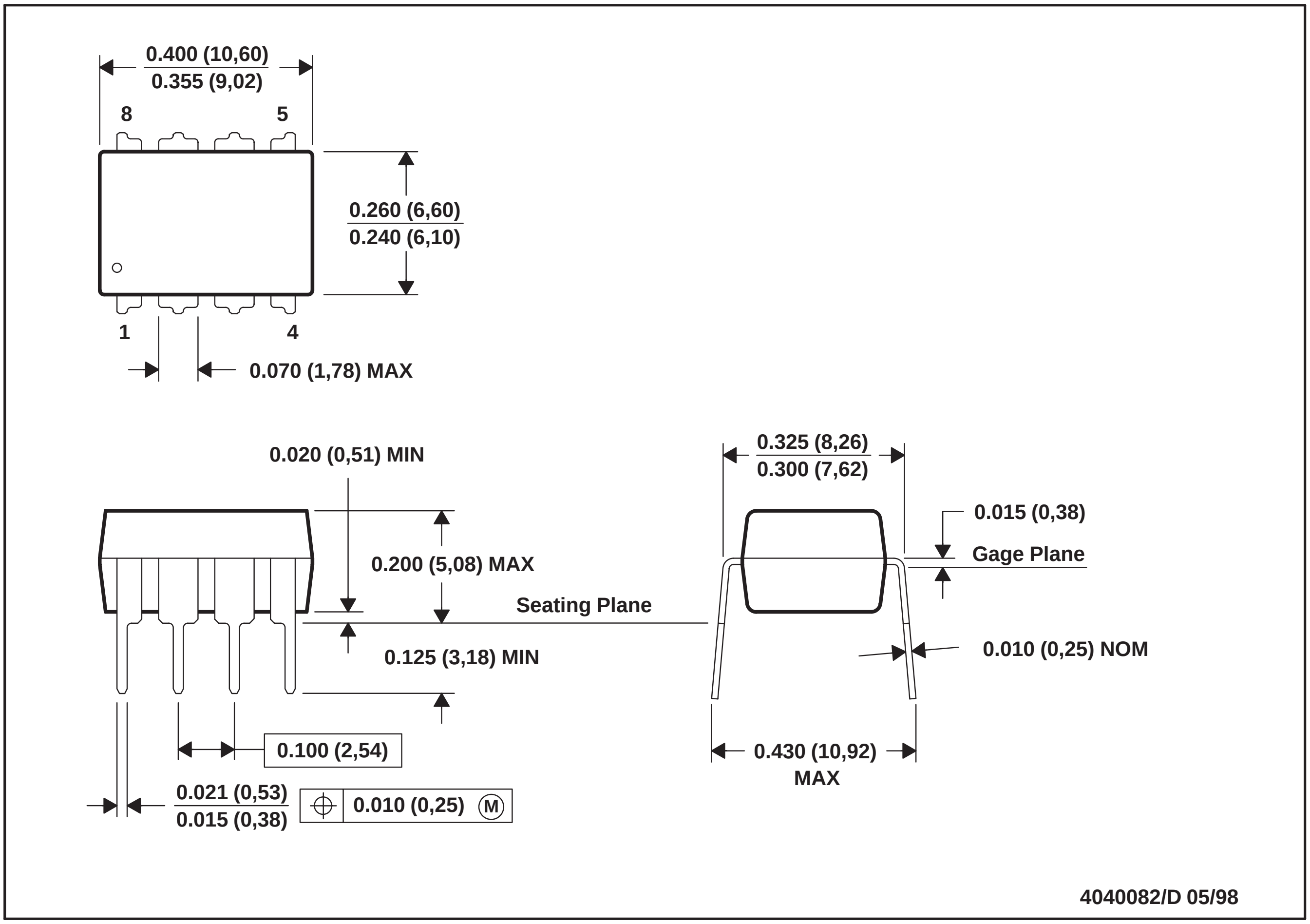
P_D = Maximum power dissipation of TLV237x IC (watts)
T_{MAX} = Absolute maximum junction temperature (150°C)
T_A = Free-ambient air temperature (°C)
θ_{JA} = $\theta_{JC} + \theta_{CA}$
θ_{JC} = Thermal coefficient from junction to case
θ_{CA} = Thermal coefficient from case to ambient air (°C/W)



NOTE A: Results are with no air flow and using JEDEC Standard Low-K test PCB.

Figure 37. Maximum Power Dissipation vs Free-Air Temperature

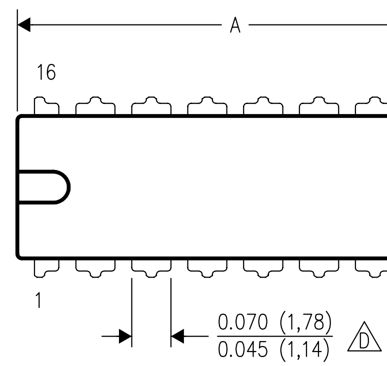
P (R-PDIP-T8) **PLASTIC DUAL-IN-LINE**



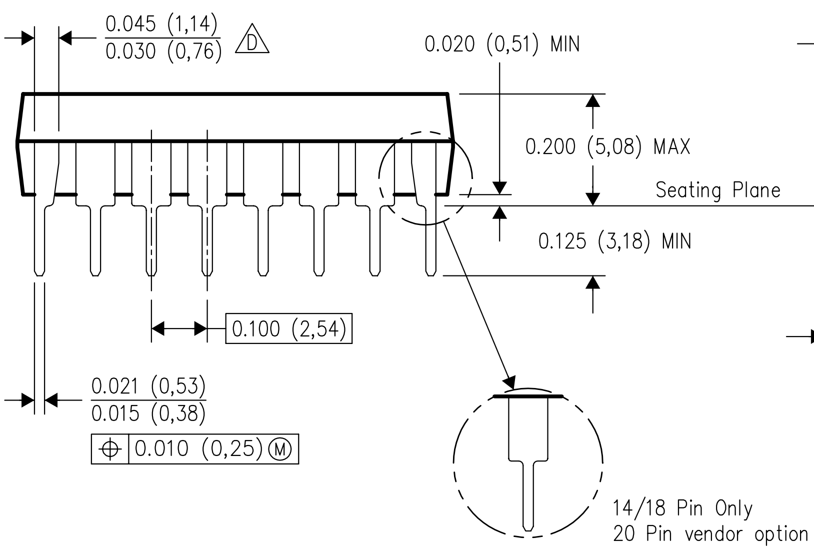
NOTES: A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. Falls within JEDEC MS-001

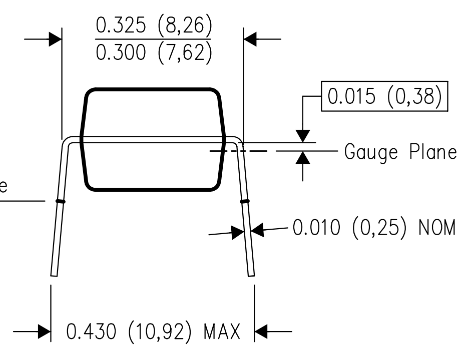
N (R–PDIP–T**) PLASTIC DUAL–IN–LINE PACKAGE

16 PINS SHOWN



DIM \ PINS **	14	16	18	20
A MAX	0.775 (19,69)	0.775 (19,69)	0.920 (23,37)	1.060 (26,92)
A MIN	0.745 (18,92)	0.745 (18,92)	0.850 (21,59)	0.940 (23,88)
C MS–001 VARIATION	AA	BB	AC	AD





4040049/E 12/2002

NOTES:
A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. Falls within JEDEC MS–001, except 18 and 20 pin minimum body length (Dim A).
D. The 20 pin end lead shoulder width is a vendor option, either half or full width.

Precision Micropower, Low Dropout Voltage References

REF19x Series

FEATURES

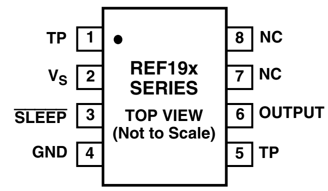
Initial Accuracy: ±2 mV Max
Temperature Coefficient: 5 ppm/°C Max
Low Supply Current: 45 μA Max
Sleep Mode: 15 μA Max
Low Dropout Voltage
Load Regulation: 4 ppm/mA
Line Regulation: 4 ppm/V
High Output Current: 30 mA
Short-Circuit Protection

APPLICATIONS

Portable Instrumentation
A/D and D/A Converters
Smart Sensors
Solar Powered Applications
Loop Current Powered Instrumentations

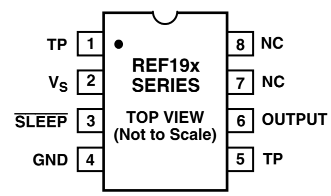
PIN CONFIGURATIONS

8-Lead SOIC and TSSOP (S Suffix and RU Suffix)



NC = NO CONNECT
TP PINS ARE FACTORY TEST POINTS, NO USER CONNECTION

8-Lead PDIP (P Suffix)



NC = NO CONNECT
TP PINS ARE FACTORY TEST POINTS, NO USER CONNECTION

GENERAL DESCRIPTION

The REF19x series precision band gap voltage references use a patented temperature drift curvature correction circuit and laser trimming of highly stable thin-film resistors to achieve a very low temperature coefficient and a high initial accuracy.

The REF19x series is made up of micropower, low dropout voltage (LDV) devices providing a stable output voltage from supplies as low as 100 mV above the output voltage and consuming less than 45 μA of supply current. In sleep mode, which is enabled by applying a low TTL or CMOS level to the $\overline{\text{SLEEP}}$ pin, the output is turned off and supply current is further reduced to less than 15 μA.

The REF19x series references are specified over the extended industrial temperature range (–40°C to +85°C) with typical performance specifications over –40°C to +125°C for applications such as automotive.

All electrical grades are available in 8-lead SOIC; the PDIP and TSSOP are available only in the lowest electrical grade. Products are also available in die form.

Test Pins (TP)

The test pins, Pin 1 and Pin 5, are reserved for in-package Zener zap. To achieve the highest level of accuracy at the output, the Zener zapping technique is used to trim the output voltage. Since each unit may require a different amount of adjustment, the resistance value at the test pins will vary widely from pin to pin as well as from part to part. The user should not make any physical or electrical connections to Pin 1 and Pin 5.

Table I.

Part Number	Nominal Output Voltage (V)
REF191	2.048
REF192	2.50
REF193	3.00
REF194	4.50
REF195	5.00
REF196	3.30
REF198	4.096

REV. G

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 www.analog.com
Fax: 781/326-8703

REF198–SPECIFICATIONS

ELECTRICAL CHARACTERISTICS (@ V_S = 5.0 V, T_A = 25°C, unless otherwise noted.)

Parameter	Symbol	Condition	Min	Typ	Max	Unit
INITIAL ACCURACY[1]						
E Grade	V_O	I_{OUT} = 0 mA	4.094	4.096	4.098	V
F Grade			4.091		4.101	V
G Grade			4.086		4.106	V
LINE REGULATION[2]						
E Grade	$\Delta V_O/\Delta V_{IN}$	4.5 V ≤ V_S ≤ 15 V, I_{OUT} = 0 mA		2	4	ppm/V
F and G Grades				4	8	ppm/V
LOAD REGULATION[2]						
E Grade	$\Delta V_O/\Delta V_{LOAD}$	V_S = 5.4 V, 0 mA ≤ I_{OUT} ≤ 30 mA		2	4	ppm/mA
F and G Grades				4	8	ppm/mA
DROPOUT VOLTAGE	$V_S - V_O$	V_S = 4.6 V, I_{LOAD} = 10 mA			0.50	V
		V_S = 5.4 V, I_{LOAD} = 30 mA			1.30	V
LONG-TERM STABILITY[3]	DV_O	1,000 Hours @ 125°C		1.2		mV
NOISE VOLTAGE	e_N	0.1 Hz to 10 Hz		40		µV p-p

NOTES
[1]Initial accuracy includes temperature hysteresis effect.
[2]Line and load regulation specifications include the effect of self-heating.
[3]Long-term drift is guaranteed by 1,000 hours life test performed on three independent wafer lots at 125°C, with an LTPD of 1.3.
Specifications subject to change without notice.

ELECTRICAL CHARACTERISTICS (@ V_S = 5.0 V, –40°C ≤ T_A ≤ +85°C, unless otherwise noted.)

Parameter	Symbol	Condition	Min	Typ	Max	Unit
TEMPERATURE COEFFICIENT[1, 2]						
E Grade	TCV_O/°C	I_{OUT} = 0 mA		2	5	ppm/°C
F Grade				5	10	ppm/°C
G Grade[3]				10	25	ppm/°C
LINE REGULATION[4]						
E Grade	$\Delta V_O/\Delta V_{IN}$	4.5 V ≤ V_S ≤ 15 V, I_{OUT} = 0 mA		5	10	ppm/V
F and G Grades				10	20	ppm/V
LOAD REGULATION[4]						
E Grade	$\Delta V_O/\Delta V_{LOAD}$	V_S = 5.4 V, 0 mA ≤ I_{OUT} ≤ 25 mA		5	10	ppm/mA
F and G Grades				10	20	ppm/mA
DROPOUT VOLTAGE	$V_S - V_O$	V_S = 4.6 V, I_{LOAD} = 10 mA			0.50	V
		V_S = 5.4 V, I_{LOAD} = 25 mA			1.30	V
$\overline{\text{SLEEP}}$ PIN						
Logic High Input Voltage	V_H		2.4			V
Logic High Input Current	I_H				–8	µA
Logic Low Input Voltage	V_L				0.8	V
Logic Low Input Current	I_L				–8	µA
SUPPLY CURRENT		No Load			45	µA
Sleep Mode		No Load			15	µA

NOTES
[1]For proper operation, a 1 µF capacitor is required between the output pin and the GND pin of the device.
[2]TCV_O is defined as the ratio of output change with temperature variation to the specified temperature range expressed in ppm/°C.

$$TCV_O = (V_{MAX} - V_{MIN})/\, V_O(T_{MAX} - T_{MIN}).$$

[3]Guaranteed by characterization.
[4]Line and load regulation specifications include the effect of self-heating.
Specifications subject to change without notice.

REF198–SPECIFICATIONS

ELECTRICAL CHARACTERISTICS (@ V_S = 5.0 V, –40°C ≤ T_A ≤ +125°C, unless otherwise noted.)

Parameter	Symbol	Condition	Min	Typ	Max	Unit
TEMPERATURE COEFFICIENT[1, 2]						
E Grade	TCV_O/°C	I_{OUT} = 0 mA		2		ppm/°C
F Grade				5		ppm/°C
G Grade[3]				10		ppm/°C
LINE REGULATION[4]						
E Grade	$\Delta V_O/\Delta V_{IN}$	4.5 V ≤ V_S ≤ 15 V, I_{OUT} = 0 mA		5		ppm/V
F and G Grades				10		ppm/V
LOAD REGULATION[4]						
E Grade	$\Delta V_O/\Delta V_{LOAD}$	V_S = 5.6 V, 0 mA ≤ I_{OUT} ≤ 20 mA		5		ppm/mA
F and G Grades				10		ppm/mA
DROPOUT VOLTAGE	$V_S - V_O$	V_S = 4.7 V, I_{LOAD} = 10 mA			0.60	V
		V_S = 5.6 V, I_{LOAD} = 20 mA			1.50	V

NOTES
[1]For proper operation, a 1 µF capacitor is required between the output pin and the GND pin of the device.
[2]TCV_O is defined as the ratio of output change with temperature variation to the specified temperature range expressed in ppm/°C.

$$TCV_O = (V_{MAX} - V_{MIN}) / V_O(T_{MAX} - T_{MIN}).$$

[3]Guaranteed by characterization.
[4]Line and load regulation specifications include the effect of self-heating.
Specifications subject to change without notice.

WAFER TEST LIMITS (@ I_{LOAD} = 0 mA, T_A = 25°C, unless otherwise noted.)

Parameter	Symbol	Condition	Limit	Unit
INITIAL ACCURACY				
REF191	V_O		2.043/2.053	V
REF192			2.495/2.505	V
REF193			2.990/3.010	V
REF194			4.495/4.505	V
REF195			4.995/5.005	V
REF196			3.290/3.310	V
REF198			4.091/4.101	V
LINE REGULATION	$\Delta V_O/\Delta V_{IN}$	(V_O + 0.5 V) < V_{IN} < 15 V, I_{OUT} = 0 mA	15	ppm/V
LOAD REGULATION	$\Delta V_O/\Delta I_{LOAD}$	0 mA < I_{LOAD} < 30 mA, V_{IN} = (V_O + 1.3 V)	15	ppm/mA
DROPOUT VOLTAGE	V_O – V+	I_{LOAD} = 10 mA	1.25	V
		I_{LOAD} = 30 mA	1.55	V
$\overline{\text{SLEEP}}$ MODE INPUT				
Logic Input High	V_{IH}		2.4	V
Logic Input Low	V_{IL}		0.8	V
SUPPLY CURRENT	V_{IN} = 15 V	No Load	45	µA
Sleep Mode		No Load	15	µA

For proper operation, a 1 µF capacitor is required between the output pins and the GND pin of the REF19x. Electrical tests and 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 qualifications through sample lot assembly and testing.

ABSOLUTE MAXIMUM RATINGS[1, 2]

Supply Voltage . . . . –0.3 V, +18 V
Output to GND . . . . –0.3 V, V_S + 0.3 V
Output to GND Short-Circuit Duration . . . . Indefinite
Storage Temperature Range
  P, S Package . . . . –65°C to +150°C
Operating Temperature Range
  REF19x . . . . –40°C to +85°C
Junction Temperature Range
  P, S Package . . . . –65°C to +150°C
Lead Temperature Range (Soldering 60 sec) . . . . 300°C

Package Type	θ_{JA}[3]	θ_{JC}	Unit
8-Lead PDIP (P)	103	43	°C/W
8-Lead SOIC (S)	158	43	°C/W
8-Lead TSSOP (RU)	240	43	°C/W

NOTES
[1] Absolute maximum rating applies to both DICE and packaged parts, unless otherwise noted.
[2] Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.
[3] θ_{JA} is specified for worst-case conditions, i.e., θ_{JA} is specified for device in socket for PDIP, and θ_{JA} is specified for device soldered in circuit board for SOIC package.

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 REF19x 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.

ORDERING GUIDE

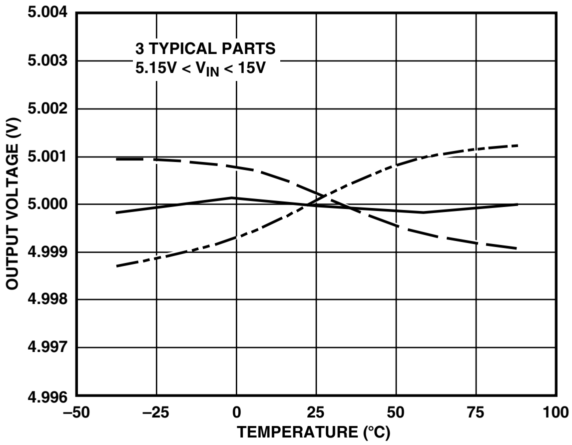
Model	Temperature Range	Package Description	Package Option	Minimum Quantities/ Reel
REF191ES	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	
REF191ES-REEL	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	2,500
REF191GP	–40°C to +85°C	8-Lead PDIP	P-Suffix (N-8	
REF191GS	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	
REF191GS-REEL7	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000
REF192ES	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	
REF192ES-REEL	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	2,500
REF192ES-REEL7	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000
REF192FS	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	
REF192FS-REEL	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	2,500
REF192FS-REEL7	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000
REF192FSZ-REEL7*	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000
REF192GP	–40°C to +85°C	8-Lead PDIP	P-Suffix (N-8)	
REF192GRU	–40°C to +85°C	8-Lead TSSOP	RU-8	
REF192GRU-REEL7	–40°C to +85°C	8-Lead TSSOP	RU-8	1,000
REF192GS	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	
REF192GS-REEL	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	2,500
REF192GS-REEL7	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000
REF192GSZ-REEL7*	–40°C to +85°C	8-Lead SOIC	S-Suffix (R-8)	1,000

ORDERING GUIDE (continued)

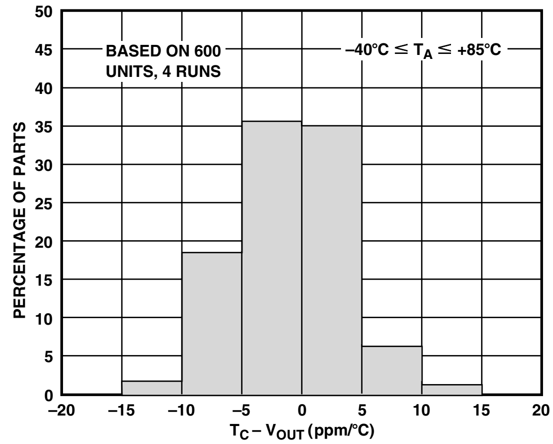
Model	Temperature Range	Package Description	Package Option	Minimum Quantities/ Reel
REF193GS	–40°C to +85°C	8-Lead SOIC	R-8	
REF193GS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF194ES	–40°C to +85°C	8-Lead SOIC	R-8	
REF194ES-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF194ESZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF194ESZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF194FS	–40°C to +85°C	8-Lead SOIC	R-8	
REF194FSZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF194GP	–40°C to +85°C	8-Lead PDIP	N-8	
REF194GS	–40°C to +85°C	8-Lead SOIC	R-8	
REF194GS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF194GS-REEL7	–40°C to +85°C	8-Lead SOIC	R-8	1,000
REF194GSZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF195ES	–40°C to +85°C	8-Lead SOIC	R-8	
REF195ES-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF195ESZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF195ESZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF195FS	–40°C to +85°C	8-Lead SOIC	R-8	
REF195FS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF195FSZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF195FSZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF195GP	–40°C to +85°C	8-Lead PDIP	N-8	
REF195GRU	–40°C to +85°C	8-Lead TSSOP	RU-8	
REF195GRU-REEL7	–40°C to +85°C	8-Lead TSSOP	RU-8	1,000
REF195GS	–40°C to +85°C	8-Lead SOIC	R-8	
REF195GS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF195GS-REEL7	–40°C to +85°C	8-Lead SOIC	R-8	1,000
REF195GSZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF195GSZ-REEL7*	–40°C to +85°C	8-Lead SOIC	R-8	1,000
REF196GRU-REEL7	–40°C to +85°C	8-Lead TSSOP	RU-8	1,000
REF196GS	–40°C to +85°C	8-Lead SOIC	R-8	
REF196GS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF196GSZ-REEL7*	–40°C to +85°C	8-Lead SOIC	R-8	1,000
REF198ES	–40°C to +85°C	8-Lead SOIC	R-8	
REF198ES-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF198ESZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF198ESZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF198ESZ-REEL7*	–40°C to +85°C	8-Lead SOIC	R-8	1,000
REF198FS	–40°C to +85°C	8-Lead SOIC	R-8	
REF198FS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF198FSZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF198GP	–40°C to +85°C	8-Lead PDIP	N-8	
REF198GRU	–40°C to +85°C	8-Lead TSSOP	RU-8	
REF198GRU-REEL7	–40°C to +85°C	8-Lead TSSOP	RU-8	1,000
REF198GRUZ*	–40°C to +85°C	8-Lead TSSOP	RU-8	
REF198GRUZ-REEL*	–40°C to +85°C	8-Lead TSSOP	RU-8	2,500
REF198GS	–40°C to +85°C	8-Lead SOIC	R-8	
REF198GS-REEL	–40°C to +85°C	8-Lead SOIC	R-8	2,500
REF198GSZ*	–40°C to +85°C	8-Lead SOIC	R-8	
REF198GSZ-REEL*	–40°C to +85°C	8-Lead SOIC	R-8	2,500

*Z = Pb-free part.

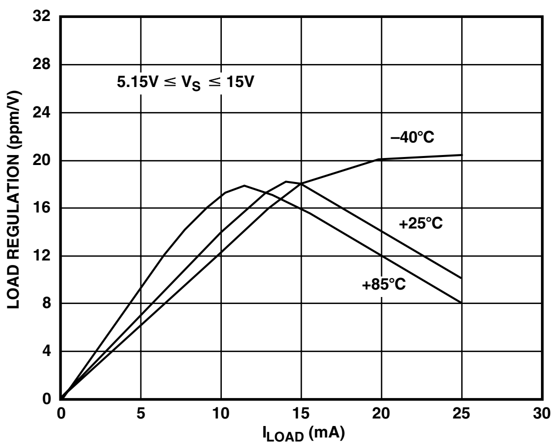
REF19x Series–Typical Performance Characteristics



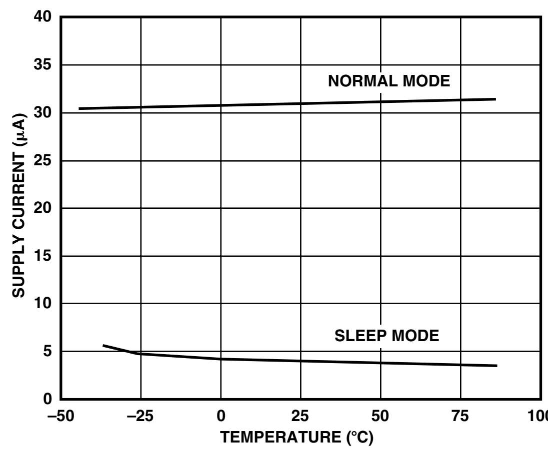
TPC 1. REF195 Output Voltage vs. Temperature



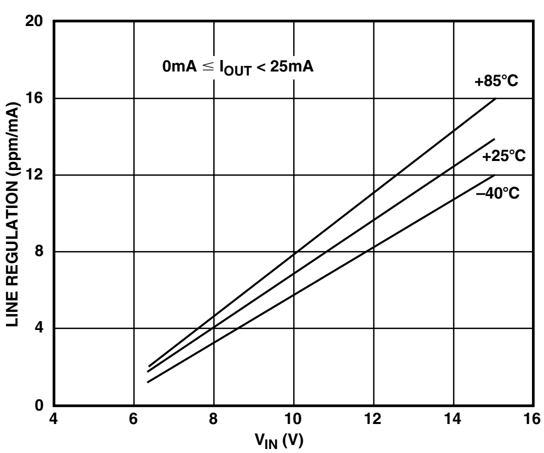
TPC 4. T_C – V_{OUT} Distribution



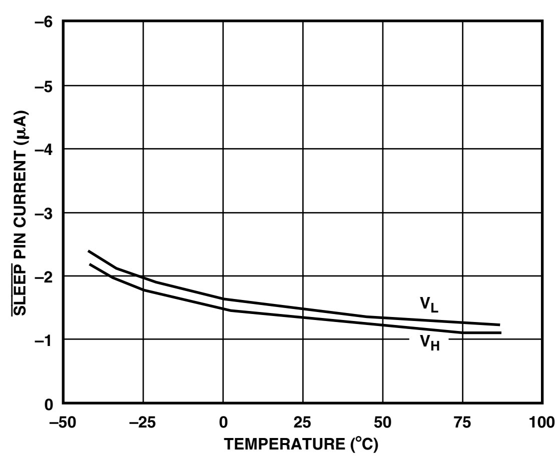
TPC 2. REF195 Load Regulation vs. I_{LOAD}



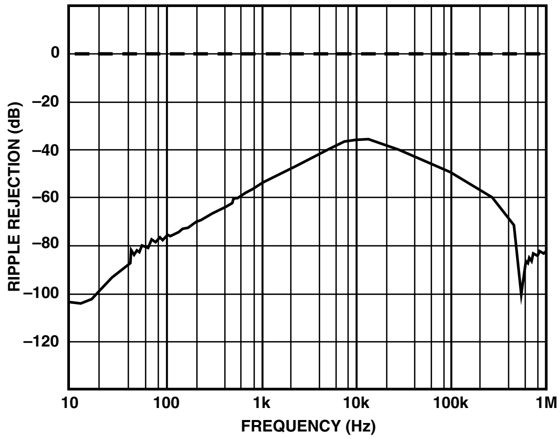
TPC 5. Quiescent Current vs. Temperature



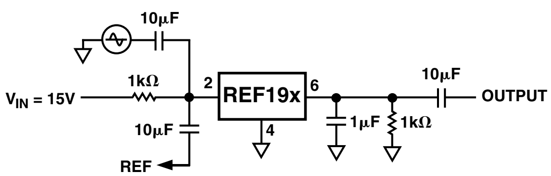
TPC 3. REF195 Line Regulation vs. V_{IN}



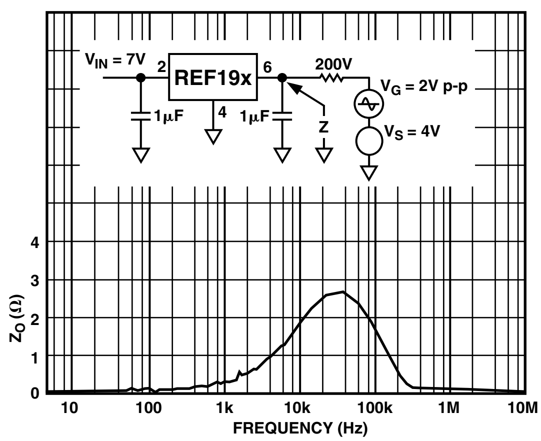
TPC 6. $\overline{SLEEP}$ Pin Current vs. Temperature



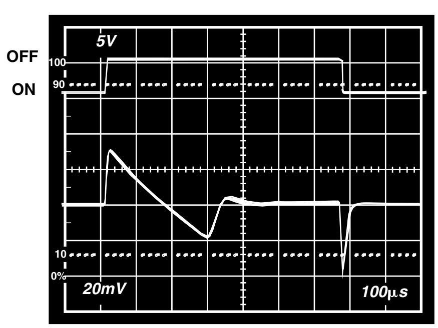
TPC 7a. Ripple Rejection vs. Frequency



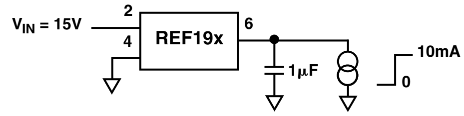
TPC 7b. Ripple Rejection vs. Frequency Measurement Circuit



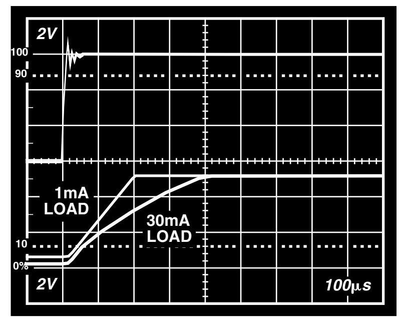
TPC 8. Output Impedance vs. Frequency



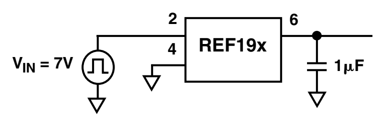
TPC 9a. Load Transient Response



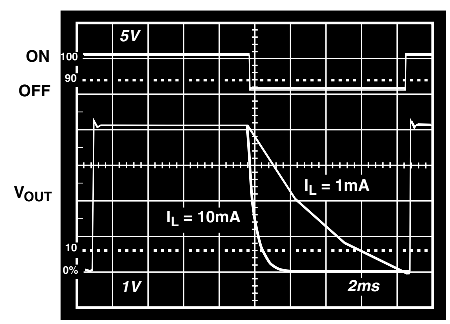
TPC 9b. Load Transient Response Measurement Circuit



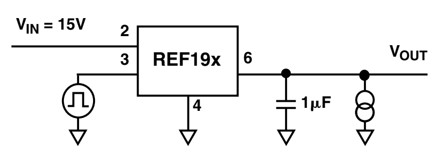
TPC 10a. Power ON Response Time



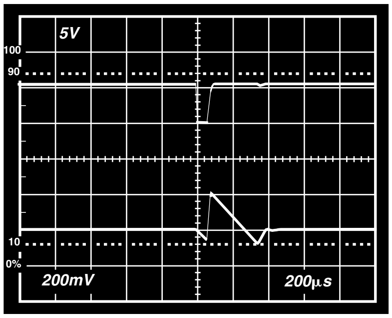
TPC 10b. Power ON Response Time Measurement Circuit



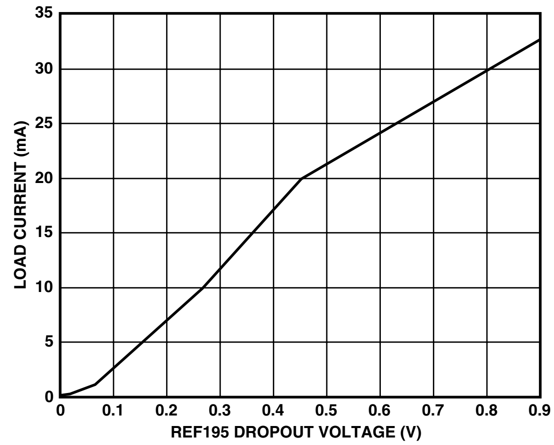
TPC 11a. $\overline{\text{SLEEP}}$ Response Time



TPC 11b. $\overline{\text{SLEEP}}$ Response Time Measurement Circuit



TPC 12. Line Transient Response



TPC 13. Load Current vs. Dropout Voltage

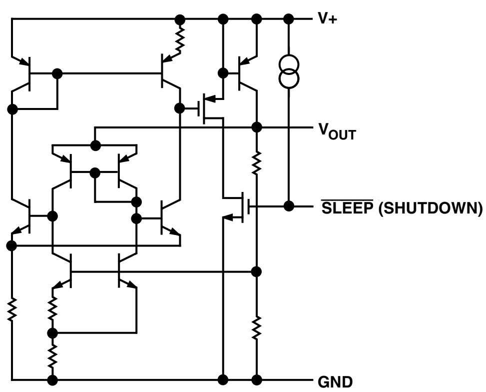


Figure 1. Simplified Schematic

APPLICATIONS SECTION

Output Short-Circuit Behavior

The REF19x family of devices is totally protected from damage due to accidental output shorts to GND or to V+. In the event of an accidental short-circuit condition, the reference device will shut down and limit its supply current to 40 mA.

Device Power Dissipation Considerations

The REF19x family of references is capable of delivering load currents to 30 mA with an input voltage that ranges from 3.3 V to 15 V. When these devices are used in applications with large input voltages, care should be exercised to avoid exceeding these devices' maximum internal power dissipation. Exceeding the published specifications for maximum power dissipation or junction temperature could result in premature device failure. The following formula should be used to calculate a device's maximum junction temperature or dissipation:

$$P_D = \frac{T_J - T_A}{\theta_{JA}}$$

In this equation, T_J and T_A are the junction and ambient temperatures, respectively, P_D is the device power dissipation, and θ_{JA} is the device package thermal resistance.

Output Voltage Bypassing

For stable operation, low dropout voltage regulators and references generally require a bypass capacitor connected from their V_{OUT} pins to their GND pins. Although the REF19x family of references is capable of stable operation with capacitive loads exceeding 100 µF, a 1 µF capacitor is sufficient to guarantee rated performance. The addition of a 0.1 µF ceramic capacitor in parallel with the bypass capacitor will improve load current transient performance. For best line voltage transient performance, it is recommended that the voltage inputs of these devices be bypassed with a 10 µF electrolytic capacitor in parallel with a 0.1 µF ceramic capacitor.

Sleep Mode Operation

All REF19x devices include a sleep capability that is TTL/CMOS level compatible. Internally, a pull-up current source to V_{IN} is connected at the $\overline{SLEEP}$ pin. This permits the $\overline{SLEEP}$ pin to be driven from an open collector/drain driver. A logic low or a 0 V condition on the $\overline{SLEEP}$ pin is required to turn off the output stage. During sleep, the output of the references becomes a high impedance state where its potential would then be determined by external circuitry. If the sleep feature is not used, it is recommended that the $\overline{SLEEP}$ pin be connected to V_{IN} (Pin 2).

Basic Voltage Reference Connections

The circuit in Figure 2 illustrates the basic configuration for the REF19x family of references. Note the 10 µF/0.1 µF bypass network on the input and the 1 µF/0.1 µF bypass network on the output. It is recommended that no connections be made to Pins 1, 5, 7, and 8. If the sleep feature is not required, Pin 3 should be connected to V_{IN}.

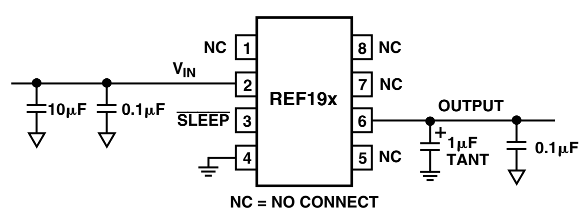


Figure 2. Basic Voltage Reference Configuration

Membrane Switch Controlled Power Supply

With output load currents in the tens of mA, the REF19x family of references can operate as a low dropout power supply in hand-held instrument applications. In the circuit shown in Figure 3, a membrane ON/OFF switch is used to control the operation of the reference. During an initial power-on condition, the $\overline{SLEEP}$ pin is held to GND by the 10 kΩ resistor. Recall that this condition disables (read: three-state) the REF19x output. When the membrane ON switch is pressed, the $\overline{SLEEP}$ pin is momentarily pulled to V_{IN}, enabling the REF19x output. At this point, current through the 10 kΩ is reduced and the internal current source connected to the $\overline{SLEEP}$ pin takes control. Pin 3 assumes and remains at the same potential as V_{IN}. When the membrane OFF switch is pressed, the $\overline{SLEEP}$ pin is momentarily connected to GND, which once again disables the REF19x output.

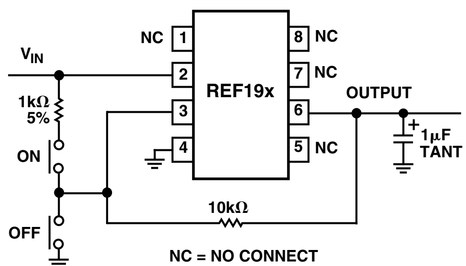
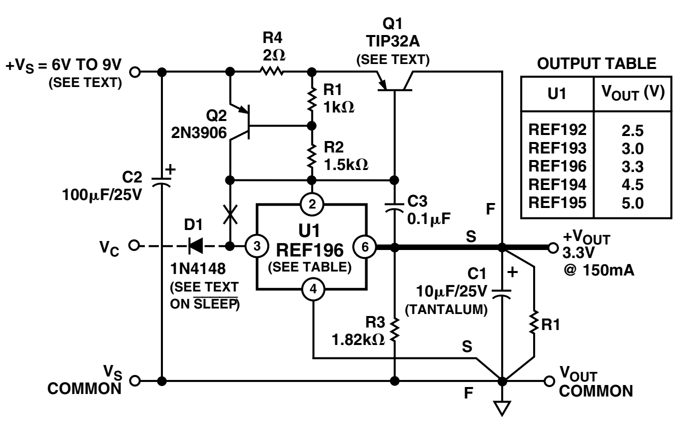


Figure 3. Membrane Switch Controlled Power Supply

Current-Boosted References with Current Limiting

While the 30 mA rated output current of the REF19x series is higher than typical of other reference ICs, it can be boosted to higher levels if desired with the addition of a simple external PNP transistor, as shown in Figure 4. Full-time current limiting is used for protection of the pass transistor against shorts.



U1	V_{OUT} (V)
REF192	2.5
REF193	3.0
REF196	3.3
REF194	4.5
REF195	5.0

Figure 4. A Boosted 3.3 V Reference with Current Limiting

In this circuit, the power supply current of reference U1 flowing through R1 to R2 develops a base drive for Q1, whose collector provides the bulk of the output current. With a typical gain of 100 in Q1 for 100 mA to 200 mA loads, U1 is never required to furnish more than a few mA, so this factor minimizes temperature-related drift. Short-circuit protection is provided by Q2, which clamps drive to Q1 at about 300 mA of load current with values as shown. With this separation of control and power functions, dc stability is optimum, allowing best advantage use of premium grade REF19x devices for U1. Of course, load management should still be exercised. A short, heavy, low DCR (dc resistance) conductor should be used from U1 to 6 to the V_{OUT} sense point S, where the collector of Q1 connects to the load, point F.

Because of the current limiting configuration, the dropout voltage circuit is raised about 1.1 V over that of the REF19x devices, due to the V_{BE} of Q1 and the drop across current sense resistor R4. However, overall dropout is typically still low enough to allow operation of a 5 V to 3.3 V regulator/reference using the REF196 for U1 as noted, with a V_S as low as 4.5 V and a load current of 150 mA.

The requirement for a heat sink on Q1 depends on the maximum input voltage and short-circuit current. With V_S = 5 V and a 300 mA current limit, the worst-case dissipation of Q1 is 1.5 W, less than the TO-220 package 2 W limit. However, if smaller TO-39 or TO-5 packaged devices, such as the 2N4033, are used, the current limit should be reduced to keep maximum dissipation below the package rating. This is accomplished by simply raising R4.

A tantalum output capacitor is used at C1 for its low ESR (equivalent series resistance), and the higher value is required for stability. Capacitor C2 provides input bypassing and can be an ordinary electrolytic.

Shutdown control of the booster stage is shown as an option, and when used, some cautions are needed. Because of the additional active devices in the V_S line to U1, direct drive to Pin 3 does not work as with an unbuffered REF19x device. To enable shutdown control, the connection from U1 to U2 is broken at the X, and diode D1 then allows a CMOS control source V_C to drive U1 to 3 for ON/OFF operation. Startup from shutdown is not as clean under heavy load as it is in basic REF19x series and can require several milliseconds under load. Nevertheless, it is still effective and can fully control 150 mA loads. When shutdown control is used, heavy capacitive loads should be minimized.

A Negative Precision Reference without Precision Resistors

In many current-output CMOS DAC applications where the output signal voltage must be of the same polarity as the reference voltage, it is often required to reconfigure a current-switching DAC into a voltage-switching DAC through the use of a 1.25 V reference, an op amp, and a pair of resistors. Using a current-switching DAC directly requires an additional operational amplifier at the output to reinvert the signal. A negative voltage reference is then desirable because an additional operational amplifier is not required for either reinversion (current-switching mode) or amplification (voltage-switching mode) of the DAC output voltage. In general, any positive voltage reference can be converted into a negative voltage reference through the use of an operational amplifier and a pair of matched resistors in an inverting configuration. The disadvantage to that approach is that the largest single source of error in the circuit is the relative matching of the resistors used.

The circuit illustrated in Figure 5 avoids the need for tightly matched resistors by using an active integrator circuit. In this circuit, the output of the voltage reference provides the input drive for the integrator. The integrator, to maintain circuit equilibrium, adjusts its output to establish the proper relationship between the reference's V_{OUT} and GND. Thus, any desired negative output voltage can be chosen by simply substituting for the appropriate reference IC. The sleep feature is maintained in the circuit with the simple addition of a PNP transistor and a 10 kΩ resistor. One caveat with this approach should be mentioned: although rail-to-rail output amplifiers work best in the application, these operational amplifiers require a finite amount (mV) of headroom when required to provide any load current. The choice for the circuit's negative supply should take this issue into account.

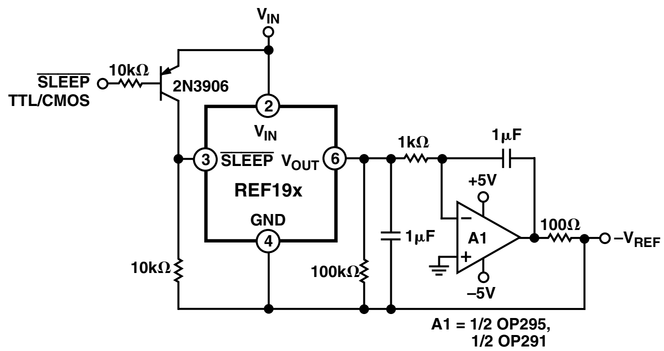


Figure 5. A Negative Precision Voltage Reference Uses No Precision Resistors

Stacking Reference ICs for Arbitrary Outputs

Some applications may require two reference voltage sources that are a combined sum of standard outputs. The circuit in Figure 6 shows how this stacked output reference can be implemented.

OUTPUT TABLE

U1/U2	V_{OUT1} (V)	V_{OUT2} (V)
REF192/REF192	2.5	5.0
REF192/REF194	2.5	7.0
REF192/REF195	2.5	7.5

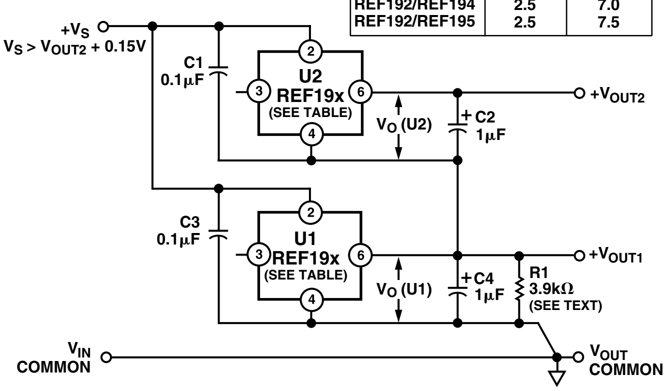


Figure 6. Stacking Voltage References with the REF19x

Two reference ICs are used, fed from a common unregulated input, V_S. The outputs of the individual ICs are simply connected in series as shown, which provides two output voltages, V_{OUT1} and V_{OUT2}. V_{OUT1} is the terminal voltage of U1, while V_{OUT2} is the sum of this voltage and the terminal voltage of U2. U1 and U2 are simply chosen for the two voltages that supply the required outputs (see Table I). If, for example, both U1 and U2 are REF192s, the two outputs are 2.5 V and 5.0 V.

While this concept is simple, some cautions are needed. Since the lower reference circuit must sink a small bias current from U2 (50 μA to 100 μA), plus the base current from the series PNP output transistor in U2, either the external load of U1 or R1 must provide a path for this current. If the U1 minimum load is not well defined, Resistor R1 should be used, set to a value that will conservatively pass 600 μA of current with the applicable V_{OUT1} across it. Note that the two U1 and U2 reference circuits are locally treated as macrocells, each having its own bypasses at input and output for best stability. Both U1 and U2 in this circuit can source dc currents up to their full rating. The minimum input voltage, V_S, is determined by the sum of the outputs, V_{OUT2}, plus the dropout voltage of U2.

A related variation on stacking two 3-terminal references is shown in Figure 6, where U1, a REF192, is stacked with a 2-terminal reference diode such as the AD589. Like the 3-terminal stacked reference above, this circuit provides two outputs, V_{OUT1} and V_{OUT2}, which are the individual terminal voltages of D1 and U1, respectively. Here this is 1.235 and 2.5, which provides a V_{OUT2} of 3.735 V. When using 2-terminal reference diodes, such as D1, the rated minimum and maximum device currents must be observed and the maximum load current from V_{OUT1} can be no greater than the current set up by R1 and $V_{O(U1)}$. In the case with $V_{O(U1)}$ equal to 2.5 V, R1 provides a 500 μA bias to D1, so the maximum load current available at V_{OUT1} is 450 μA or less.

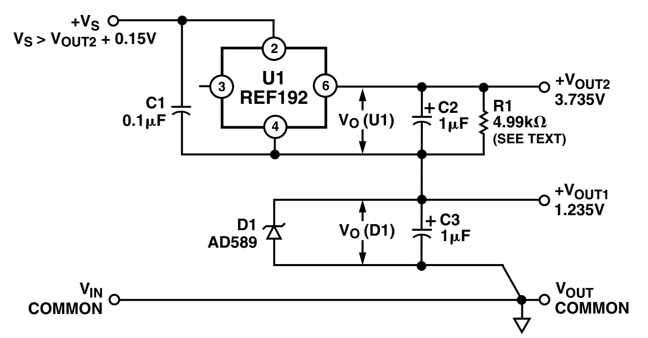


Figure 7. Stacking Voltage References with the REF19x

A Precision Current Source

Many times, in low power applications, the need arises for a precision current source that can operate on low supply voltages. As shown in Figure 8, any one of the devices in the REF19x family of references can be configured as a precision current source. The circuit configuration illustrated is a floating current source with a grounded load. The reference's output voltage is bootstrapped across R_{SET}, which sets the output current into the load. With this configuration, circuit precision is maintained for load currents in the range from the reference's supply current (typically 30 μA) to approximately 30 mA. The low dropout voltage of these devices maximizes the current source's output voltage compliance without excess headroom.

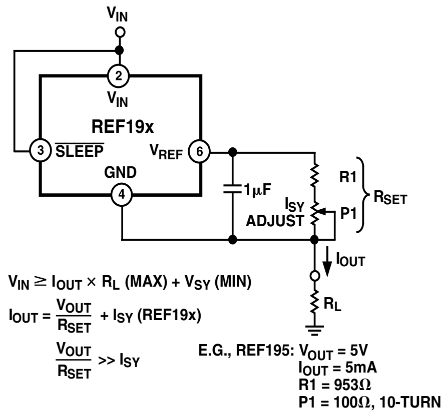


Figure 8. A Low Dropout, Precision Current Source

The circuit's governing equations are

$$V_{IN} = I_{OUT} \times R_L(Max) + V_{SY}(Min,\ REF19x)$$

$$I_{OUT} = \frac{V_{OUT}}{R_{SET}} + I_{SY}(REF19x)$$

$$\frac{V_{OUT}}{R_{SET}} \rangle\rangle I_{SY}(REF19x)$$

Switched Output 5 V/3.3 V Reference

Applications often require digital control of reference voltages, selecting between one stable voltage and a second. With the sleep feature inherent to the REF19x series, switched output reference configurations are easily implemented with relatively little additional hardware.

The circuit of Figure 9 illustrates the general technique, which takes advantage of the output "wire-OR" capability of the REF19x device family. When OFF, a REF19x device is effectively an open circuit at the output node with respect to the power supply. When ON, a REF19x device can source current up to its current rating, but sink only a few µA (essentially just the relatively low current of the internal output scaling divider). As a result, for two devices wired together at their common outputs, the output voltage is simply that of the ON device. The OFF state device will draw a small standby current of 15 µA (max), but otherwise will not interfere with operation of the ON device, which can operate to its full current rating. Note that the two devices in the circuit conveniently share both input and output capacitors, and with CMOS logic drive, it is power efficient.

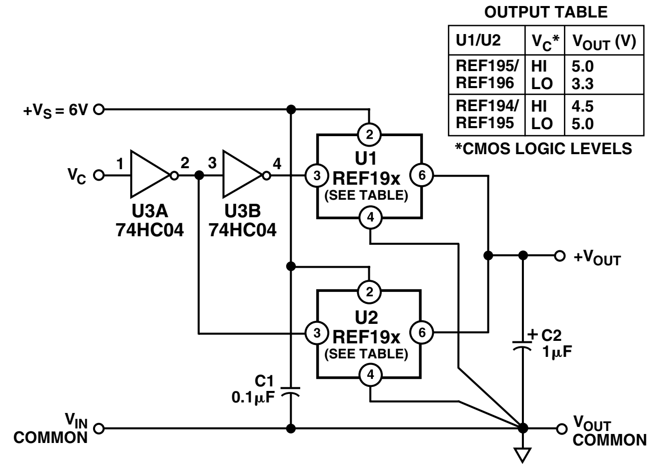


Figure 9. Switched Output Reference

Using dissimilar REF19x series devices with this configuration allows logic selection between the U1/U2 specified terminal voltages. For example, with U1 (a REF195) and U2 (a REF196), as noted in the table in Figure 9, changing the CMOS compatible V_C logic control voltage from HI to LO selects between a nominal output of 5.000 V and 3.300 V and vice versa. Other REF19x family units can also be used for U1/U2, with similar operation in a logic sense, but with outputs as per the individual paired devices (see table again). Of course, the exact output voltage tolerance, drift, and overall quality of the reference voltage will be consistent with the grade of individual U1 and U2 devices.

Because of the nature of the wire-OR, there is one application caveat that should be understood about this circuit. Since U1 and U2 can only *source* current effectively, negative going output voltage changes, which require the *sinking* of current, will necessarily take longer than positive going changes. In practice, this means that the circuit is quite fast when undergoing a transition from 3.3 V to 5 V, but the transition from 5 V to 3.3 V will take longer. Exactly how much longer will be a function of the load resistance, R_L, seen at the output and the typical 1 µF value of C2. In general, a conservative transition time here will be on the order of several milliseconds for load resistances in the range of 100 Ω to 1 kΩ. Note that for highest accuracy at the new output voltage, several time constants should be allowed (>7.6 time constants for <1/2 LSB error @ 10 bits, for example).

Kelvin Connections

In many portable instrumentation applications where PC board cost and area go hand-in-hand, circuit interconnects are very often narrow. These narrow lines can cause large voltage drops if the voltage reference is required to provide load currents to various functions. In fact, a circuit's interconnects can exhibit a typical line resistance of 0.45 mΩ/square (1 oz. Cu, for example). In those applications where these devices are configured as low dropout voltage regulators, these wiring voltage drops can become a large source of error. To circumvent this problem, force and sense connections can be made to the reference through the use of an operational amplifier, as shown in Figure 10. This method provides a means by which the effects of wiring resistance voltage drops can be eliminated. Load currents flowing through wiring resistance produce an I-R error ($I_{LOAD} \times R_{WIRE}$) at the load. However, the Kelvin connection overcomes the problem by including the wiring resistance within the forcing loop of the op amp. Since the op amp senses the load voltage, op amp loop control forces the output to compensate for the wiring error and to produce the correct voltage at the load. Depending on the reference device chosen, operational amplifiers that can be used in this application are the OP295, the OP292, and the OP183.

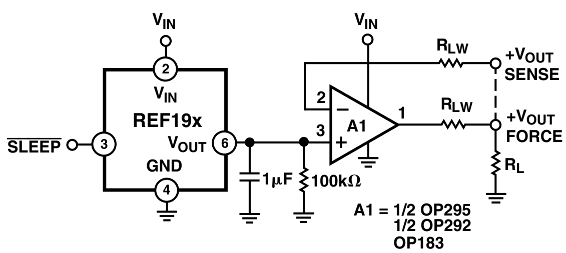


Figure 10. A Low Dropout, Kelvin Connected Voltage Reference

A Fail-Safe 5 V Reference

Some critical applications require a reference voltage to be maintained constant, even with a loss of primary power. The low standby power of the REF19x series and the switched output capability allow a fail-safe reference configuration to be implemented rather easily. This reference maintains a tight output voltage tolerance for either a primary power source (ac line derived) or a standby (battery derived) power source, automatically switching between the two as the power conditions change.

The circuit in Figure 11 illustrates the concept, which borrows from the switched output idea of Figure 8, again using the REF19x device family output wire-OR capability. In this case, since a constant 5 V reference voltage is desired for all conditions, two REF195 devices are used for U1 and U2, with their ON/OFF switching controlled by the presence or absence of the primary dc supply source, V_S. V_{BAT} is a 6 V battery backup source that supplies power to the load only when V_S fails. For normal (V_S present) power conditions, V_{BAT} sees only the 15 µA (max) standby current drain of U1 in its OFF state.

In operation, it is assumed that for all conditions either U1 or U2 is ON and a 5 V reference output is available. With this voltage constant, a scaled down version is applied to the comparator IC U3, providing a fixed 0.5 V input to the (–) input for all power conditions. The R1 to R2 divider provides a signal to the U3 (+) input proportional to V_S, which switches U3 and U1/U2 dependent upon the absolute level of V_S. Op amp U3 is configured here as a comparator with hysteresis, which provides for clean, noise-free output switching. This hysteresis is important to eliminate rapid switching at the threshold due to V_S ripple. Further, the device chosen is the AD820, a rail-to-rail output device that provides HI and LO output states within a few mV of V_S and ground for accurate thresholds and compatible drive for U2 for all V_S conditions. R3 provides positive feedback for circuit hysteresis, changing the threshold at the (+) input as a function of U3's output.

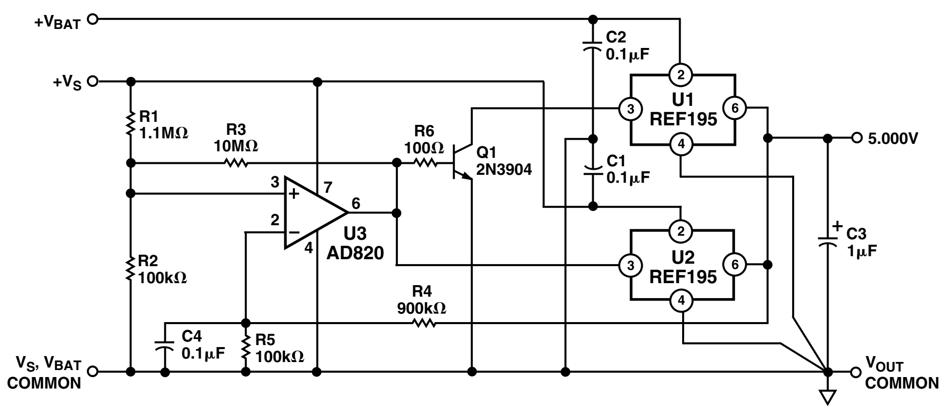


Figure 11. A Fail-Safe 5 V Reference

For V_S levels lower than the LOWER threshold, U3's output is low, thus U2 and Q1 are OFF, while U1 is ON. For V_S levels higher than the UPPER threshold, the situation reverses, with U1 OFF and both U2 and Q1 ON. In the interest of battery power conservation, all of the comparison switching circuitry is powered from V_S and is arranged so that when V_S fails, the default output comes from U1.

For the R1 to R3 values as shown, the LOWER/UPPER V_S switching thresholds are approximately 5.5 V and 6 V, respectively. These can obviously be changed to suit other V_S supplies, as can the REF19x devices used for U1 and U2, over a range of 2.5 V to 5 V of output. U3 can operate down to a V_S of 3.3 V, which is generally compatible with all family devices.

A Low Power, Strain Gage Circuit

As shown in Figure 12, the REF19x family of references can be used in conjunction with low supply voltage operational amplifiers, such as the OP492 and the OP283, in a self-contained strain gage circuit. In this circuit, the REF195 was used as the core of this low power, strain gage circuit. Other references can be easily accommodated by changing circuit element values. The references play a dual role as the voltage regulator to provide the supply voltage requirements of the strain gage and the operational amplifiers as well as a precision voltage reference for the current source used to stimulate the bridge. A distinct feature of the circuit is that it can be remotely controlled ON or OFF by digital means via the $\overline{\text{SLEEP}}$ pin.

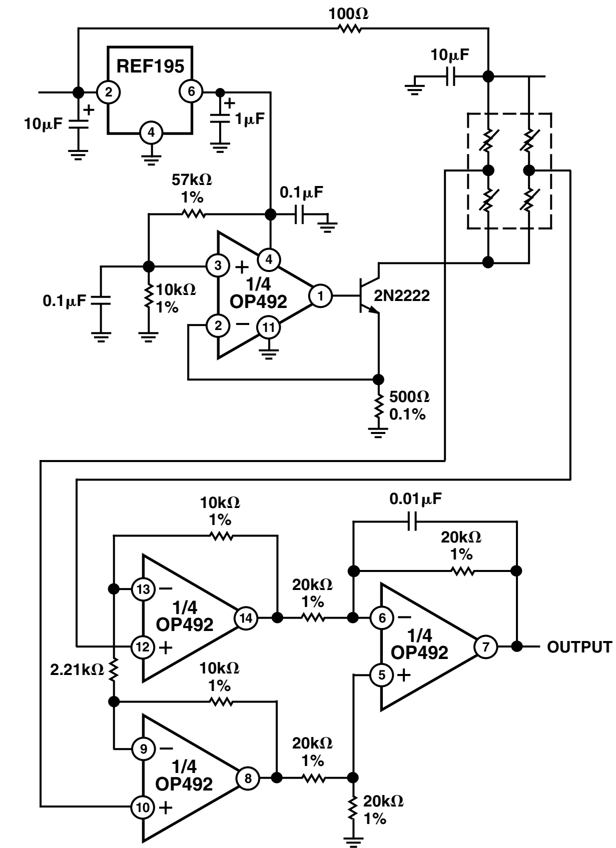
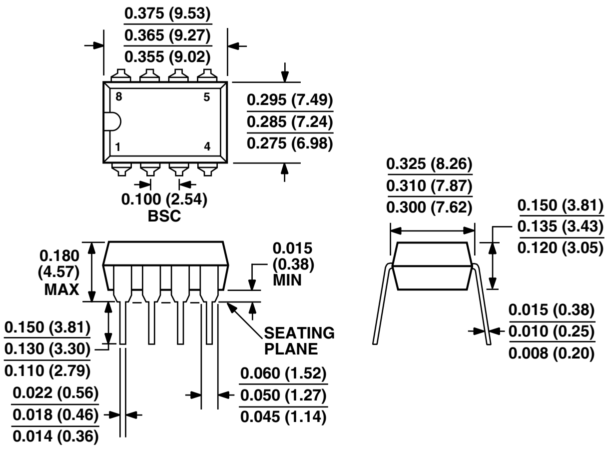


Figure 12. A Low Power, Strain Gage Circuit

OUTLINE DIMENSIONS

8-Lead Plastic Dual In-Line Package [PDIP] (N-8) P-Suffix

Dimensions shown in inches and (millimeters)

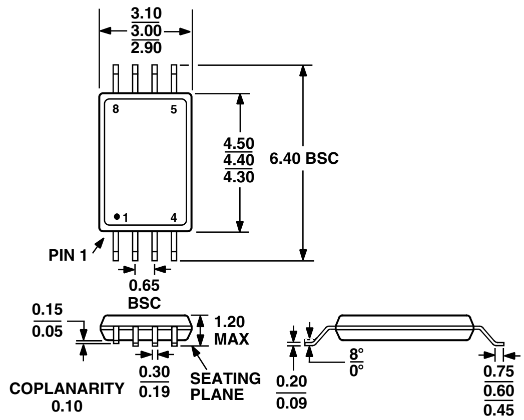


COMPLIANT TO JEDEC STANDARDS MO-095AA

CONTROLLING DIMENSIONS ARE IN INCHES; MILLIMETER DIMENSIONS (IN PARENTHESES) ARE ROUNDED-OFF INCH EQUIVALENTS FOR REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN

8-Lead Thin Shrink Small Outline Package [TSSOP] (RU-8)

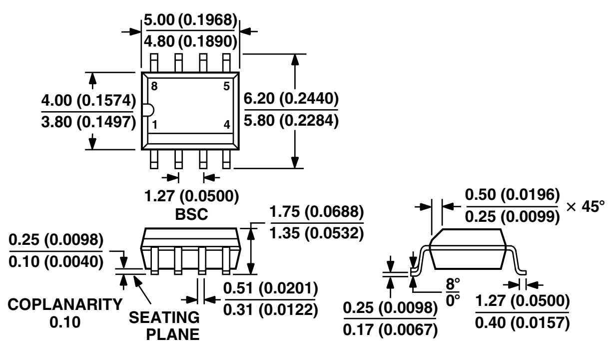
Dimensions shown in millimeters



COMPLIANT TO JEDEC STANDARDS MO-153AA

8-Lead Standard Small Outline Package [SOIC] Narrow Body (R-8) S-Suffix

Dimensions shown in millimeters and (inches)



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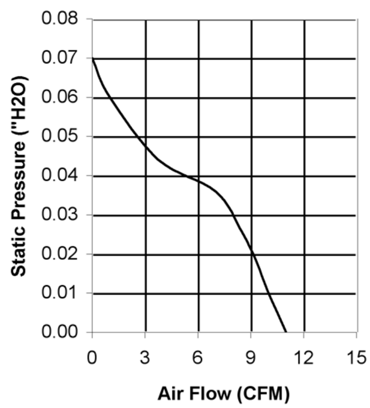
OA60 Series

60 x 60 x 30mm
(2.36"x 2.36" x 1.18")

Frame
Diecast Aluminum

Impeller
PBT, UL94V-0 Thermoplastic

Power Connection
Two lead wires 300mm (12")



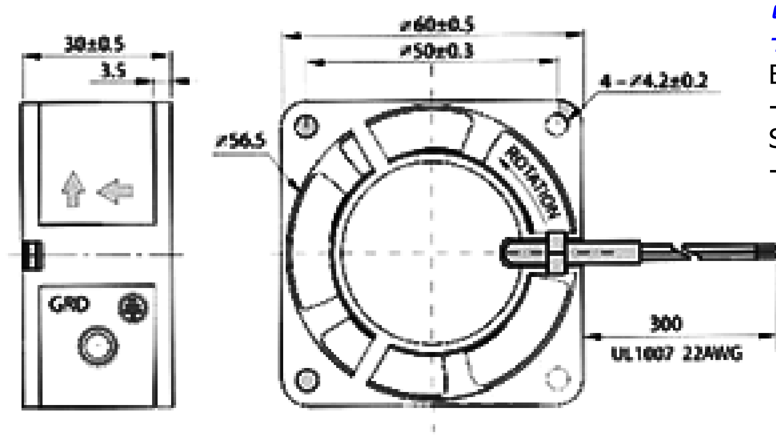
Finger Guard: G60-4
Plastic Guard: G60P
Aluminum Filter: WMG 60M
Filter Kit: GRM60-30, GRM60-45

Model Number	Speed (RPM)	Airflow (CFM)	dB (Noise)	Volts	Voltage Range	Watts	Max. Static Pressure (ìH2O)
OA60AP-11-1WB	3100	11	28	115	80~130	4	0.07
OA60AP-22-1WB	3100	11	28	230	160~260	4	0.07

Motor
Shaded pole, Impedance and polarity protected

Dielectric Strength
1 minute @ 1500VAC, 50/60Hz

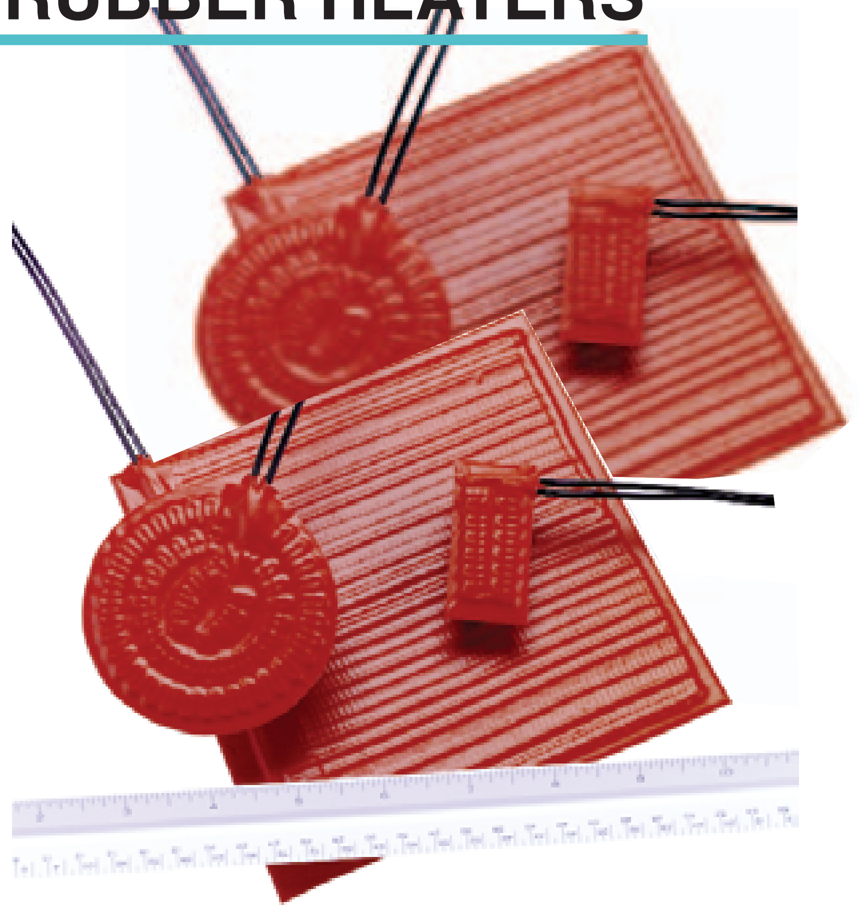
Life Expectancy
Ball Bearing
60,000 hours (L10 at 40C)
Sleeve Bearing
30,000 hours (L10 at 40C)



Drawing for dimensional reference only.

Operating Temperature
Ball Bearing
-20C ~ +80C
Sleeve Bearing
-10C ~ +50C

SILICON RUBBER HEATERS



- Flexible
- Continuous Exposure to Temperatures up to 232°C (450°F)
- Moisture and Chemical Resistant
- Wide Variety of Sizes and Shapes
- Optional Presensitive Adhesive Backing

Environmental factors of many industrial heating applications require a product with the ability to withstand chemicals, moisture and abusive treatment. These same applications also require rapid heat up, steady temperature maintenance, and uniform heat distribution. For applications such as these, OMEGA silicone rubber heating blankets are the best products available.

OMEGA silicone rubber heating blankets are used for freeze protection, process temperature control, melting of solids, temperature heat-up or maintenance. Whether installed in Original Equipment or in the field, our silicone heaters will provide the durability required.

- Moisture Resistant
- Chemical Resistant
- Radiation Resistant

Approvals:

UR pending

SPECIFICATIONS

Operating voltage: 120 Vac.

Leads:
30.48 cm (12") Teflon standard (*Additional length available)

Heating Element: laminated between two layers of, 0.015 mil, fiberglass reinforced silicone rubber

Silicone Rubber Density:
16.8 oz/yd^2 (0.06 grams/cm^2) per layer

Maximum Energized Exposure Temperature: 232°C (450°F)

Maximum De-energized Exposure Temperature: 260°C (500°F)

Minimum Exposure Temperature: -51°C (-60°F)

Dielectric Strength: > 2000 volts

Additional Lead Length: 12" is standard, heaters are also available with 96" leads may be custom ordered. To specify additional lead length add the suffix "**-096**" to the end of the part number and **$45** to the price. Examples:

ROUND
Standard 12" leads:
SRMU0206D, $30.70.
Optional 96" leads:
SRMU0206D-096, $75.70.

SQUARE/RECTANGULAR
Standard 12" leads:
SRMU020606, $28.60.
Optional 96" leads:
SRMU020606-096, $73.60.

Round SRMU Heat Blankets

To Order *(Specify Model Number)*

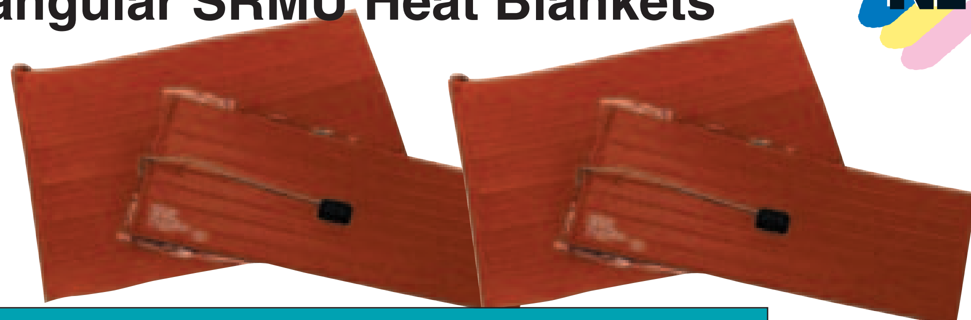
Diameter cm (")	2.5Watts/in^2 (0.39 Watts/cm^2)	5Watts/in^2 (0.78 Watts/cm^2)	10 Watts/in^2 (1.55 Watts/cm^2)	Price no PSA	Price with PSA*
7.62 (3)	SRMU0203D	SRMU0503D	SRMU1003D	$20.10	$22.20
10.16 (4)	SRMU0204D	SRMU0504D	SRMU1004D	24.40	26.80
12.70 (5)	SRMU0205D	SRMU0505D	SRMU1005D	29.70	32.60
15.24 (6)	SRMU0206D	SRMU0506D	SRMU1006D	30.70	33.80
17.78 (7)	SRMU0207D	SRMU0507D	SRMU1007D	33.90	37.30
20.32 (8)	SRMU0208D	SRMU0508D	SRMU1008D	37.10	40.80
22.86 (9)	SRMU0209D	SRMU0509D	SRMU1009D	41.30	45.50
25.40 (10)	SRMU0210D	SRMU0510D	SRMU1010D	45.60	50.10
27.94 (11)	SRMU0211D	SRMU0511D	SRMU1011D	50.90	56.00
30.48 (12)	SRMU0212D	SRMU0512D	SRMU1012D	56.20	61.80

** To Order with PSA (Presensitive Adhesive) add suffix **"-P"** to Model Number.*
Ordering Example: SRMU0506D-P**, 5 Watt/in^2, 15.24 cm (6") diameter heater with pressure sensitive adhesive, **$33.80.

SILICON RUBBER HEATERS

Square/Rectangular SRMU Heat Blankets

1 to 3" Width



To Order *(Specify Model Number)*

Width cm (")	Length cm (")	2.5Watts/in^2 (0.39 Watts/cm^2)	5Watts/in^2 (0.78 Watts/cm^2)	10 Watts/in^2 (1.55 Watts/cm^2)	Price no PSA	Price with PSA*
2.54 (1)	2.54 (1)	**N/A**	**N/A**	**SRMU100101**	**$15.90**	**$17.50**
2.54 (1)	5.08 (2)	**N/A**	**SRMU050102**	**N/A**	**17.00**	**18.70**
2.54 (1)	7.62 (3)	**SRMU020103**	**SRMU050103**	**SRMU100103**	**17.00**	**18.70**
2.54 (1)	10.16 (4)	**SRMU020104**	**SRMU050104**	**SRMU100104**	**18.00**	**19.80**
2.54 (1)	12.70 (5)	**SRMU020105**	**SRMU050105**	**SRMU100105**	**19.10**	**21.00**
2.54 (1)	15.24 (6)	**SRMU020106**	**SRMU050106**	**SRMU100106**	**19.10**	**21.00**
2.54 (1)	17.78 (7)	**SRMU020107**	**SRMU050107**	**SRMU100107**	**20.10**	**22.20**
2.54 (1)	20.32 (8)	**SRMU020108**	**SRMU050108**	**SRMU100108**	**13.80**	**15.20**
2.54 (1)	22.86 (9)	**SRMU020109**	**SRMU050109**	**SRMU100109**	**14.80**	**16.30**
2.54 (1)	25.40 (10)	**SRMU020110**	**SRMU050110**	**SRMU100110**	**14.80**	**16.30**
2.54 (1)	27.94 (11)	**SRMU020111**	**SRMU050111**	**SRMU100111**	**14.80**	**16.30**
2.54 (1)	30.48 (12)	**SRMU020112**	**SRMU050112**	**SRMU100112**	**15.90**	**17.50**
2.54 (1)	45.72 (18)	**SRMU020118**	**SRMU050118**	**SRMU100118**	**18.00**	**19.80**
2.54 (1)	60.96 (24)	**SRMU020124**	**SRMU050124**	**SRMU100124**	**21.20**	**23.30**
2.54 (1)	76.20 (30)	**SRMU020130**	**SRMU050130**	**SRMU100130**	**24.30**	**24.50**
2.54 (1)	91.44 (36)	**SRMU020136**	**SRMU050136**	**SRMU100136**	**26.60**	**29.20**
2.54 (1)	106.68 (42)	**SRMU020142**	**SRMU050142**	**SRMU100142**	**28.60**	**31.50**
2.54 (1)	121.92 (48)	**SRMU020148**	**SRMU050148**	**SRMU100148**	**31.80**	**35.00**
5.08 (2)	5.08 (2)	**SRMU020202**	**SRMU050202**	**SRMU100202**	**17.00**	**18.70**
5.08 (2)	7.62 (3)	**SRMU020203**	**SRMU050203**	**SRMU100203**	**18.00**	**19.80**
5.08 (2)	10.16 (4)	**SRMU020204**	**SRMU050204**	**SRMU100204**	**18.00**	**19.80**
5.08 (2)	12.70 (5)	**SRMU020205**	**SRMU050205**	**SRMU100205**	**15.90**	**17.50**
5.08 (2)	15.24 (6)	**SRMU020206**	**SRMU050206**	**SRMU100206**	**15.90**	**17.50**
5.08 (2)	17.78 (7)	**SRMU020207**	**SRMU050207**	**SRMU100207**	**17.00**	**18.70**
5.08 (2)	20.32 (8)	**SRMU020208**	**SRMU050208**	**SRMU100208**	**18.00**	**19.80**
5.08 (2)	22.86 (9)	**SRMU020209**	**SRMU050209**	**SRMU100209**	**18.00**	**19.80**
5.08 (2)	25.40 (10)	**SRMU020210**	**SRMU050210**	**SRMU100210**	**19.10**	**21.00**
5.08 (2)	27.94 (11)	**SRMU020211**	**SRMU050211**	**SRMU100211**	**20.10**	**22.00**
5.08 (2)	30.48 (12)	**SRMU020212**	**SRMU050212**	**SRMU100212**	**20.10**	**22.00**
5.08 (2)	45.72 (18)	**SRMU020218**	**SRMU050218**	**SRMU100218**	**24.40**	**26.80**
5.08 (2)	60.96 (24)	**SRMU020224**	**SRMU050224**	**SRMU100224**	**28.60**	**31.50**
5.08 (2)	76.20 (30)	**SRMU020230**	**SRMU050230**	**SRMU100230**	**31.80**	**35.00**
5.08 (2)	91.44 (36)	**SRMU020236**	**SRMU050236**	**SRMU100236**	**36.00**	**39.60**
5.08 (2)	106.68 (42)	**SRMU020242**	**SRMU050242**	**SRMU100242**	**40.30**	**44.30**
5.08 (2)	121.92 (48)	**SRMU020248**	**SRMU050248**	**SRMU100248**	**44.50**	**49.00**
7.62 (3)	7.62 (3)	**SRMU020303**	**SRMU050303**	**SRMU100303**	**18.00**	**19.80**
7.62 (3)	10.16 (4)	**SRMU020304**	**SRMU050304**	**SRMU100304**	**19.10**	**21.00**
7.62 (3)	12.70 (5)	**SRMU020305**	**SRMU050305**	**SRMU100305**	**20.00**	**22.00**
7.62 (3)	15.24 (6)	**SRMU020306**	**SRMU050306**	**SRMU100306**	**21.20**	**23.30**
7.62 (3)	17.78 (7)	**SRMU020307**	**SRMU050307**	**SRMU100307**	**22.30**	**24.50**
7.62 (3)	20.32 (8)	**SRMU020308**	**SRMU050308**	**SRMU100308**	**23.30**	**25.50**
7.62 (3)	22.86 (9)	**SRMU020309**	**SRMU050309**	**SRMU100309**	**23.30**	**25.50**
7.62 (3)	25.40 (10)	**SRMU020310**	**SRMU050310**	**SRMU100310**	**24.40**	**26.80**
7.62 (3)	27.94 (11)	**SRMU020311**	**SRMU050311**	**SRMU100311**	**25.40**	**28.00**
7.62 (3)	30.48 (12)	**SRMU020312**	**SRMU050312**	**SRMU100312**	**26.50**	**28.70**
7.62 (3)	45.72 (18)	**SRMU020318**	**SRMU050318**	**SRMU100318**	**31.80**	**35.80**
7.62 (3)	60.96 (24)	**SRMU020324**	**SRMU050324**	**SRMU100324**	**38.20**	**42.00**
7.62 (3)	76.20 (30)	**SRMU020330**	**SRMU050330**	**SRMU100330**	**43.50**	**47.80**
7.62 (3)	91.44 (36)	**SRMU020336**	**SRMU050336**	**SRMU100336**	**48.80**	**53.60**
7.62 (3)	106.68 (42)	**SRMU020342**	**SRMU050342**	**SRMU100342**	**55.40**	**60.60**
7.62 (3)	121.92 (48)	**SRMU020348**	**SRMU050348**	**SRMU100348**	**60.40**	**66.50**

M

** To Order with PSA (Pressure Sensitive Adhesive) add suffix **"-P"** to Model Number.*

*To custom order 96" leads, add suffix **"-096"** to model number and **$45** to price.*

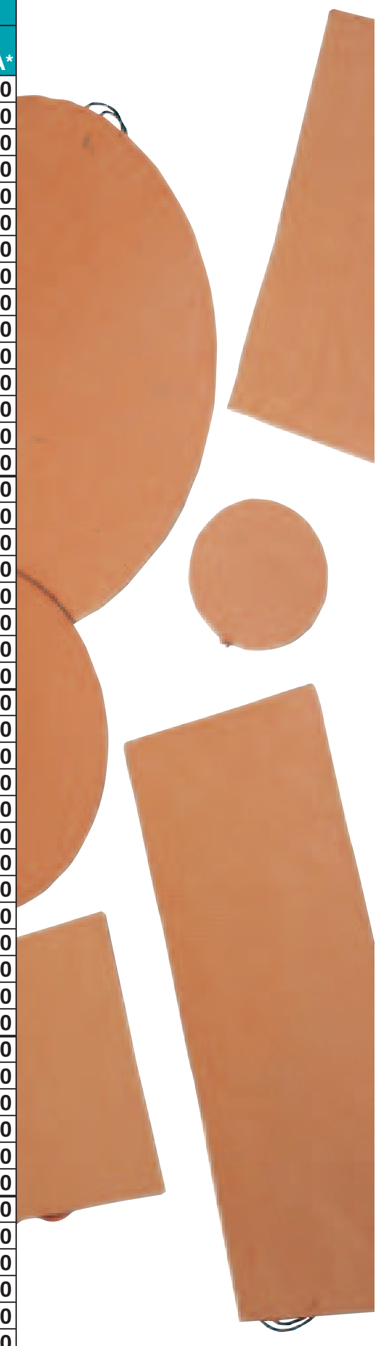
Ordering Example:
SRMU020306-P**, 10 watt/in^2 4 x 6" heater with PSA (pressure sensitive adhesive), **$23.30.

SILICON RUBBER HEATERS

Square/Rectangular SRMU Heat Blankets
4 to 8" Width

To Order *(Specify Model Number)*

Width cm (")	Length cm (")	2.5Watts/in^2 (0.39 Watts/cm^2)	5Watts/in^2 (0.78 Watts/cm^2)	10 Watts/in^2 (1.55 Watts/cm^2)	Price no PSA	Price with PSA*
10.16 (4)	10.16 (4)	SRMU020404	SRMU050404	SRMU100404	$22.30	$24.50
10.16 (4)	12.70 (5)	SRMU020405	SRMU050405	SRMU100405	23.30	25.70
10.16 (4)	15.24 (6)	SRMU020406	SRMU050406	SRMU100406	25.40	28.00
10.16 (4)	17.78 (7)	SRMU020407	SRMU050407	SRMU100407	26.50	29.20
10.16 (4)	20.32 (8)	SRMU020408	SRMU050408	SRMU100408	27.60	30.30
10.16 (4)	22.86 (9)	SRMU020409	SRMU050409	SRMU100409	28.60	31.50
10.16 (4)	25.40 (10)	SRMU020410	SRMU050410	SRMU100410	29.70	32.60
10.16 (4)	27.94 (11)	SRMU020411	SRMU050411	SRMU100411	30.70	33.80
10.16 (4)	30.48 (12)	SRMU020412	SRMU050412	SRMU100412	31.80	35.00
10.16 (4)	45.72 (18)	SRMU020418	SRMU050418	SRMU100418	39.20	43.10
10.16 (4)	60.96 (24)	SRMU020424	SRMU050424	SRMU100424	46.60	51.30
10.16 (4)	76.20 (30)	SRMU020430	SRMU050430	SRMU100430	54.10	59.50
10.16 (4)	91.44 (36)	SRMU020436	SRMU050436	SRMU100436	60.40	66.50
10.16 (4)	106.68 (42)	SRMU020442	SRMU050442	SRMU100442	67.80	74.80
10.16 (4)	121.92 (48)	SRMU020448	SRMU050448	N/A	75.30	82.80
12.70 (5)	12.70 (5)	SRMU020505	SRMU050505	SRMU100505	27.60	30.30
12.70 (5)	15.24 (6)	SRMU020506	SRMU050506	SRMU100506	28.60	31.50
12.70 (5)	17.78 (7)	SRMU020507	SRMU050507	SRMU100507	29.70	32.60
12.70 (5)	20.32 (8)	SRMU020508	SRMU050508	SRMU100508	31.80	35.00
12.70 (5)	22.86 (9)	SRMU020509	SRMU050509	SRMU100509	32.90	36.10
12.70 (5)	25.40 (10)	SRMU020510	SRMU050510	SRMU100510	33.90	37.30
12.70 (5)	27.94 (11)	SRMU020511	SRMU050511	SRMU100511	35.00	38.50
12.70 (5)	30.48 (12)	SRMU020512	SRMU050512	SRMU100512	37.10	40.80
15.24 (6)	15.24 (6)	SRMU020606	SRMU050606	SRMU100606	28.60	31.50
15.24 (6)	17.78 (7)	SRMU020607	SRMU050607	SRMU100607	29.70	32.60
15.24 (6)	20.32 (8)	SRMU020608	SRMU050608	SRMU100608	30.70	33.80
15.24 (6)	22.86 (9)	SRMU020609	SRMU050609	SRMU100609	31.80	35.00
15.24 (6)	25.40 (10)	SRMU020610	SRMU050610	SRMU100610	32.90	36.10
15.24 (6)	27.94 (11)	SRMU020611	SRMU050611	SRMU100611	33.90	37.30
15.24 (6)	30.48 (12)	SRMU020612	SRMU050612	SRMU100612	36.00	39.60
15.24 (6)	45.72 (18)	SRMU020618	SRMU050618	SRMU100618	43.50	47.80
15.24 (6)	60.96 (24)	SRMU020624	SRMU050624	SRMU100624	50.90	56.00
15.24 (6)	76.20 (30)	SRMU020630	SRMU050630	N/A	58.30	64.10
15.24 (6)	91.44 (36)	SRMU020636	SRMU050636	N/A	65.70	72.30
15.24 (6)	106.68 (42)	SRMU020642	SRMU050642	N/A	73.10	80.50
15.24 (6)	121.92 (48)	SRMU020648	SRMU050648	N/A	80.60	88.60
17.78 (7)	17.78 (7)	SRMU020707	SRMU050707	SRMU100707	30.70	33.80
17.78 (7)	20.32 (8)	SRMU020708	SRMU050708	SRMU100708	32.90	36.10
17.78 (7)	22.86 (9)	SRMU020709	SRMU050709	SRMU100709	33.90	37.30
17.78 (7)	25.40 (10)	SRMU020710	SRMU050710	SRMU100710	35.00	38.50
17.78 (7)	27.94 (11)	SRMU020711	SRMU050711	SRMU100711	37.10	40.80
17.78 (7)	30.48 (12)	SRMU020712	SRMU050712	SRMU100712	38.20	42.00
20.32 (8)	20.32 (8)	SRMU020808	SRMU050808	SRMU100808	33.90	37.30
20.32 (8)	22.86 (9)	SRMU020809	SRMU050809	SRMU100809	36.00	39.60
20.32 (8)	25.40 (10)	SRMU020810	SRMU050810	SRMU100810	37.10	40.80
20.32 (8)	27.94 (11)	SRMU020811	SRMU050811	SRMU100811	39.20	43.10
20.32 (8)	30.48 (12)	SRMU020812	SRMU050812	SRMU100812	40.30	44.30
20.32 (8)	45.72 (18)	SRMU020818	SRMU050818	SRMU100818	50.90	56.00
20.32 (8)	60.69 (24)	SRMU020824	SRMU050824	N/A	60.40	66.50
20.32 (8)	76.20 (30)	SRMU020830	SRMU050830	N/A	71.00	78.10
20.32 (8)	91.44 (36)	SRMU020836	SRMU050836	N/A	80.60	88.60
20.32 (8)	106.68 (42)	SRMU020842	SRMU050842	N/A	91.20	100.30
20.32 (8)	121.92 (48)	SRMU020848	SRMU050848	N/A	100.70	110.80



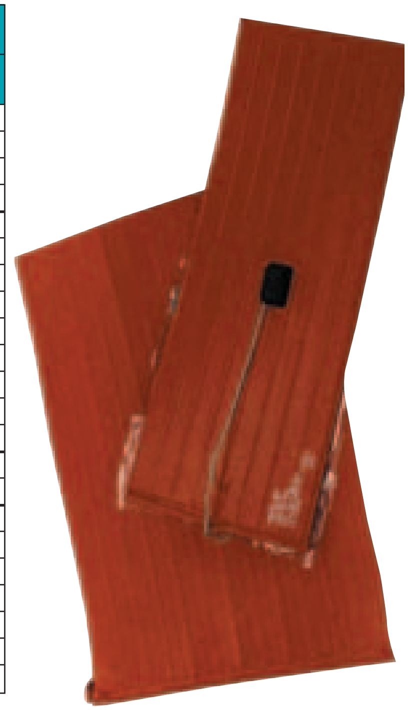
** To order with PSA (Pressure Sensitive Adhesive) add suffix **"-P"** to Model Number.*
*To custom order 96" leads, add suffix **"-096"** to model number and **$45** to price.*
Ordering Example: SRMU100608-P**, 10 watt/in^2 6 x 8" heater with PSA (pressure sensitive adhesive), **$33.80.

SILICON RUBBER HEATERS

Square/Rectangular SRMU Heat Blankets
9 to 12" Width

To Order ***(Specify Model Number)***

Width cm (")	Length cm (")	2.5Watts/in^2 (0.39 Watts/cm^2)	5Watts/in^2 (0.78 Watts/cm^2)	10 Watts/in^2 (1.55 Watts/cm^2)	Price no PSA	Price with PSA*
22.86 (9)	22.86 (9)	SRMU020909	SRMU050909	SRMU100909	$37.10	$40.80
22.86 (9)	25.40 (10)	SRMU020910	SRMU050910	SRMU100910	39.20	43.10
22.86 (9)	27.94 (11)	SRMU020911	SRMU050911	SRMU100911	41.30	45.50
22.86 (9)	30.48 (12)	SRMU020912	SRMU050912	SRMU100912	43.50	47.80
25.40 (10)	25.40 (10)	SRMU021010	SRMU051010	SRMU101010	41.30	42.90
25.40 (10)	27.94 (11)	SRMU021011	SRMU051011	SRMU101011	43.50	47.80
25.40 (10)	30.48 (12)	SRMU021012	SRMU051012	SRMU101012	45.60	50.10
25.40 (10)	45.72 (18)	SRMU021018	SRMU051018	N/A	58.30	64.10
25.40 (10)	60.69 (24)	SRMU021024	SRMU051024	N/A	71.00	78.10
25.40 (10)	76.20 (30)	SRMU021030	SRMU051030	N/A	83.70	92.10
25.40 (10)	91.44 (36)	SRMU021036	SRMU051036	N/A	96.50	106.10
25.40 (10)	106.68 (42)	SRMU021042	N/A	N/A	109.20	120.10
25.40 (10)	121.92 (48)	SRMU021048	N/A	N/A	120.80	132.90
27.94 (11)	27.94 (11)	SRMU021111	SRMU051111	SRMU101111	45.60	50.10
27.94 (11)	30.48 (12)	SRMU021112	SRMU051112	SRMU101112	48.80	53.60
30.48 (12)	20.32 (12)	SRMU021212	SRMU051212	N/A	50.90	56.00
30.48 (12)	22.86 (18)	SRMU021218	SRMU051218	N/A	65.70	72.30
30.48 (12)	25.40 (24)	SRMU021224	SRMU051224	N/A	80.60	88.60
30.48 (12)	27.94 (30)	SRMU021230	N/A	N/A	96.50	106.10
30.48 (12)	30.48 (36)	SRMU021236	N/A	N/A	111.30	122.40
30.48 (12)	45.72 (42)	SRMU021242	N/A	N/A	126.10	138.10
30.48 (12)	60.96 (48)	SRMU021248	N/A	N/A	141.00	155.10



** To order with PSA (Pressure Sensitive Adhesive) add suffix **"-P"** to Model Number.*
*To custom order 96" leads, add suffix **"-096"** to model number and **$45** to price.*
Ordering Example: SRMU020608-P**, 2.5 watt/in^2 6 x 8" heater, **$33.80.

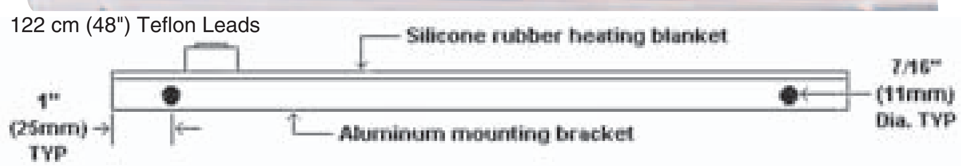
Silicon Rubber Enclosed Heaters

SREH series enclosure heaters feature our serpentine wound heating element laminated between two layers of 15 mil fiberglass reinforced silicone rubber and bonded to an aluminum mounting plate. The mounting plate comes with two 11mm (7⁄16") holes for mounting. The built-in air sensing thermostat regulates the temperature in the enclosure to prevent condensation or freezing.The SREH enclosure heaters can be mounted vertically or horizontally, however optimal control is achieved when mounted vertically.

- **Moisture resistant**
- **Chemical resistant**
- **Radiation resistant**

Approvals:
UR pending

122 cm (48") Teflon Leads



To Order ***(Specify Model Number)***

Width cm (")	Length cm (")	Total Watts	Thermostat Opens	Thermostat Closes	Model Number (120VAC)	Price
6.4 (2.5)	15.24 (6)	60	N/A	N/A	SREH600	$24
6.4 (2.5)	15.24 (6)	60	15°C (60°F)	4°C (40°F)	SREH640	76
6.4 (2.5)	15.24 (6)	60	60°C (140°F)	43°C (110°F)	SREH6110	76
6.4 (2.5)	15.24 (6)	60	82°C (180°F)	65°C (150°F)	SREH6150	76
6.4 (2.5)	30.48 (12)	120	N/A	N/A	SREH1200	31
6.4 (2.5)	30.48 (12)	120	15°C (60°F)	4°C (40°F	SREH1240	84
6.4 (2.5)	30.48 (12)	120	140°F (60°C)	43°C (110°F)	SREH12110	84
6.4 (2.5)	30.48 (12)	120	180°F (82°C)	65°C (150°F)	SREH12150	84

Ordering Example:** SREH1240, 30.48 cm (12"), 120 Watt heater with 15°C (60°F) setpoint thermostat, **$84.00

SPECIFICATIONS

Operating Voltage: 120 Vac
Leads: 122 cm (48") Teflon
Heating Element:
laminated between two layers of, 0.015 mil, fiberglass reinforced silicone rubber
Silicone Rubber Density:
16.8 oz/yd^2 (0.06 grams/cm^2) per layer
Overall Thickness: (blanket and bracket) 1/4" (0.64 cm)
Maximum Energized Exposure Temperature:
232°C (450°F)
Maximum De-energized Exposure Temperature:
260°C (500°F)
Minimum Exposure Temperature:
-51°C (-60°F)
Dielectric Strength: > 2000 volts

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