Optimizing Thermoelectric Temperature Control Systems

Thermoelectric coolers (TECs) are used in a variety of applications that require extremely stable temperature control. System design can be complex, but improved system performance can be well worth the effort. Laser diode systems that require narrow linewidths (cancer treatments, spectroscopy, etc.) combine low noise laser current sources with high performance temperature control to achieve required stabilities. Detector systems approaching the noise floor also use precision temperature control to increase responsivity and reduce noise. Small, TEC based portable refrigerators and sample coolers relieve some of the need for environmentally harmful chemical coolants.

Because of their solid state construction, these small devices are very reliable and relatively easy to use. Excellent temperature stabilities can be achieved if the system is assembled properly. Designers must have a good understanding of thermal management techniques and carefully select the thermoelectric module, temperature sensor, and controller before attempting to build high performance systems. Optimized temperature control will reduce temperature instability due to thermal transients and load changes, and in many cases, shorten the system's settling time.

This technical note will provide a practical step by step guide to thermoelectric cooler system design with rule of thumb approximations that work with most loads. As always, some loads may be different and require special considerations. We've included a basic troubleshooting guide that covers the majority of problems our customers have encountered over time.

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SYSTEM COMPONENTS

In a typical TEC system, current flow through the TEC pumps heat from one plate surface to the other (see Figure 1). Based on the Peltier effect, this makes one plate cold and the other hot. If current direction is reversed, the hot and cold sides also reverse. The TEC is mounted between the heat sink and the device being cooled with a sensor to monitor temperature. The controller uses the temperature sensor feedback to adjust the current flow through the TEC to maintain the device at the desired temperature.
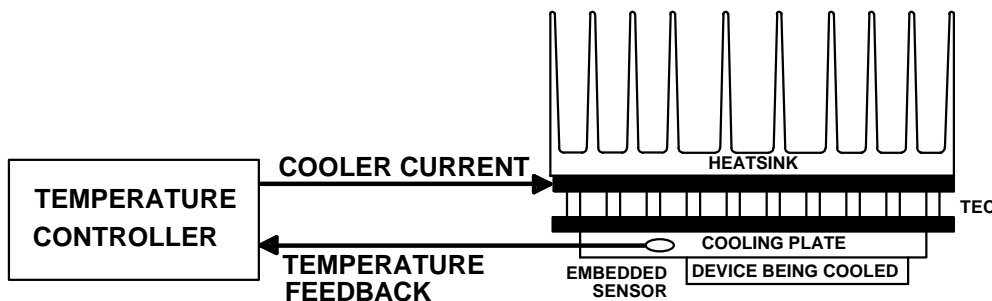

FIGURE 1. A simple thermoelectric control system uses feedback from a temperature sensor to maintain a device at constant temperature.

In the following sections, each component is reviewed in detail.

THERMOELECTRIC SELECTION

Many times designers select TEC modules without thoroughly considering the controller. Before purchasing a TEC module, make sure the controller can supply the power required to bring the device to the desired temperature and maintain a stable operating temperature. The sections on Controller Selection and Optimizing the PID Controller describe problems that may arise from selecting an incompatible TEC and controller.

When selecting a TEC, three load parameters must be defined: the maximum temperature of the TEC hot face during operation in Celsius (T_H), the minimum temperature of the TEC cold face during operation in Celsius (T_C), and the amount of heat absorbed at the cold face of the TEC in Watts (Q_C). Given these operating parameters, performance graphs from the TEC manufacturer are used to identify an appropriate cooler.

T_H is determined by the system's expected maximum ambient temperature ($T_{AMBIENT}$) and the efficiency and capacity of the heat sink assembly. For small thermal loads with sufficient heat sinking, assume that $T_H = T_{AMBIENT} + 5°C$. For larger thermal loads or if the heat sink is marginal, assume $T_H = T_{AMBIENT} + 15°C$. Typically, these estimates provide adequate margin for a good thermal design.

T_C is determined by the maximum deviation from ambient temperature and the geometry of the cooling plate. For small thermal loads, T_C can be estimated to be equal to the minimum cold temperature of the load. If the thermal load is larger, or the thermal path length from the TEC to the device being cooled is longer than 1", assume T_C is five degrees below the desired device temperature.

Q_C is determined by combining the active and passive heat loads that must be pumped from the device and cooling plate to the heat sink. The active heat load is defined as the power dissipated by the device being cooled, and is generally equal to the input power to the device. For electronic devices, the heat load power dissipation can be calculated as:

$$Q_{active} = \frac{V^2}{R} = VI = I^2R$$

where Q_{ACTIVE} is the active heat load in Watts, V is the voltage across the device in Volts, R is the device resistance in ohms, and I is the current through the device in amps.

The passive or parasitic heat loads consist of radiation, convection, and conduction. In most applications, the conduction heat loss from sensor connections and cooling plate mounting is negligible and can be ignored. The following equation determines the worst case passive heat load for most applications.

$$Q_{passive} = Q_{rad} + Q_{conv} + Q_{cond} = F\varepsilon\sigma A\left(T_H^4 - T_C^4\right) + hA(T_H - T_C) + \frac{kW}{L}(T_H - T_C)$$

F	= Shape Factor (assume a worst case value of 1)	**h**	= Convective heat transfer coefficient ($W/m^{2\circ}C$)
ε	= Emissivity (assume a worst case value of 1)		(assume the value for air at 1 atm. of 21.7)
σ	= Stefan-Boltzman constant (5.667×10^{-8} W/m^2K^4)	**k**	= thermal conductivity of the material ($W/m°C$)
A	= Area of the cooled surface (m^2)		(assume the value for copper of 386)
T_H	= Maximum temperature of the TEC hot face during operation (K)	**W**	= Cross-sectional area of the material (m^2)
T_C	= Minimum temperature of the TEC cold face during operation (K)	**L**	= Length of the heat path (m)

For example, assume we have a 3mW laser diode in a standard 9mm can package, mounted to a 1" x 1" x 1/8" square cooling plate (0.001 m^2 - top surface + 4 edges). The hot surface will be about 10°C above room temperature, and the device temperature needs to be 15°C, so T_H=35°C and T_C=15°C. If the laser diode's forward current is 50mA and the forward voltage is 1.8V, the active heat load will be:

$$Q_{active} = V_f I_f = (1.8V)(50mA) = 90mW$$

Assuming negligible heat transfer due to conduction the passive heat load will be:

$$Q_{passive} = (5.667x10^{-8})(0.001)\left|(308)^4 - (288)^4\right| + (21.7)(0.001)(308 - 288)$$
$$= 0.554 \text{ Watts}$$

The heat pumped from the TEC's cold surface is:
$$Q_C = Q_{active} + Q_{passive}$$
$$= 0.644 \text{ Watts}$$

Note that for small thermal loads, the passive heat loss is typically several times larger than the power dissipated by the device being cooled.

Given these three parameters, the performance charts from TEC manufacturers will guide you to a module with sufficient capacity. A typical single stage TEC module can maintain a maximum temperature differential of 64°C (T_H - T_C). Designs requiring larger differentials must use cascaded TEC modules (where two or more TECs are stacked on top of each other). Many manufacturers offer preassembled cascaded configurations.

CONTROLLER SELECTION

The controller's output power capacity is limited by its maximum voltage and current capacity and internal power dissipation. Thermoelectric temperature controllers have either voltage or current source outputs to drive the TEC. Because current source output stages are more common in commercially available controllers, we focus our discussion on their drive limitations. The maximum output voltage of a current source is generally referred to as "compliance voltage." A controller's compliance voltage can be calculated as:

$$V_{compliance} = \frac{P_{max}}{I_{max}}$$

The following example illustrates the constraints that compliance voltage places on driving a TEC.

Compliance Voltage Example: Consider using a controller with a 2 A, 12 W capacity with a TEC that requires 6 W (Q_C) to maintain the device at 15°C (T_C) with a 35°C heat sink temperature (T_H). We select a TEC with maximum current of 2 Amps and maximum output power of 10W, which appears to meet the load and controller requirements. Using values of T_C, T_H, and Q_C, we review the manufacturer's selection/performance graphs and determine that the TEC must be supplied with a current of 1.8 Amps at 8.5 Volts to maintain temperature. When we consider the controller's compliance voltage, we determine the incompatibility between the controller and the TEC.

$$V_{compliance} = \frac{12 Watts}{2 Amps} = 6 Volts$$

Once the TEC voltage exceeds the 6V compliance voltage limit, the output current will be a function of the compliance voltage and impedance of the TEC. In this case, the TEC will exhibit an approximate impedance of (8.5V/1.8A) or 4.7Ω. The output current will be limited to (6V/4.7Ω) or 1.3 Amps. This clearly is not sufficient current to maintain the desired temperature. A different TEC module or controller must be selected. The controller can only source its maximum current to loads with impedances less than:

$$R_{max} = \frac{6V}{2A} = 3\Omega$$

The controller's compliance voltage should be close to the V_{MAX} rating of the selected TEC for maximum use of the TEC's power pumping capacity.

Once a TEC and controller are matched to deliver the necessary power, other performance specifications should be considered. These include rated stability, temperature coefficient, control loop type, TEC protection features, and sensor compatibility.

There is no industry standard load configuration for manufacturers to rate temperature stability of controllers. Usually, the load is optimized for the controller and the stability measurement is taken at one temperature using a specific sensor. Inquiries to the manufacturer should determine the size and type of thermal load controlled and whether the testing was done in an environmental chamber or in a standard ambient air environment. Once the manufacturer's test conditions and thermal load are determined, compare them to your own system and derate the performance accordingly.

The controller's temperature coefficient will give a good indication of the system performance under normal ambient conditions. This measurement is usually specified in °C/°C or ppm/°C. Even controllers with excellent temperature coefficients will benefit from being placed in a controlled environment. To improve system performance, insulate the controller from drafts or room temperature fluctuations whenever possible.

The most common feedback configuration for high performance temperature controllers involves a combination of proportional, integral, and differential (PID) control (see "PID Controllers Explained"). Most PID controllers are designed with analog electronics because digital PID loops tend to radiate noise into the device being cooled.

The final parameter to consider is the protection offered to the TEC. The controller should provide a TEC current limit function. When this current limit is set correctly, it should limit the output current at or below I_{max} of the TEC. This protects the TEC from being damaged. As we will see in a later section, the current limit can also be used in optimizing the controllers performance.

The sensor feedback signal and sensor placement directly affect the controller's ability to maintain a stable device temperature. Most controllers can use a wide variety of sensors. The controller should be compatible with the type of sensor required by the system design.

PID LOOP CONTROLLER EXPLAINED

A typical controller can be considered in three sections: the error amplifier, the PID processor, and the output power amplifier.
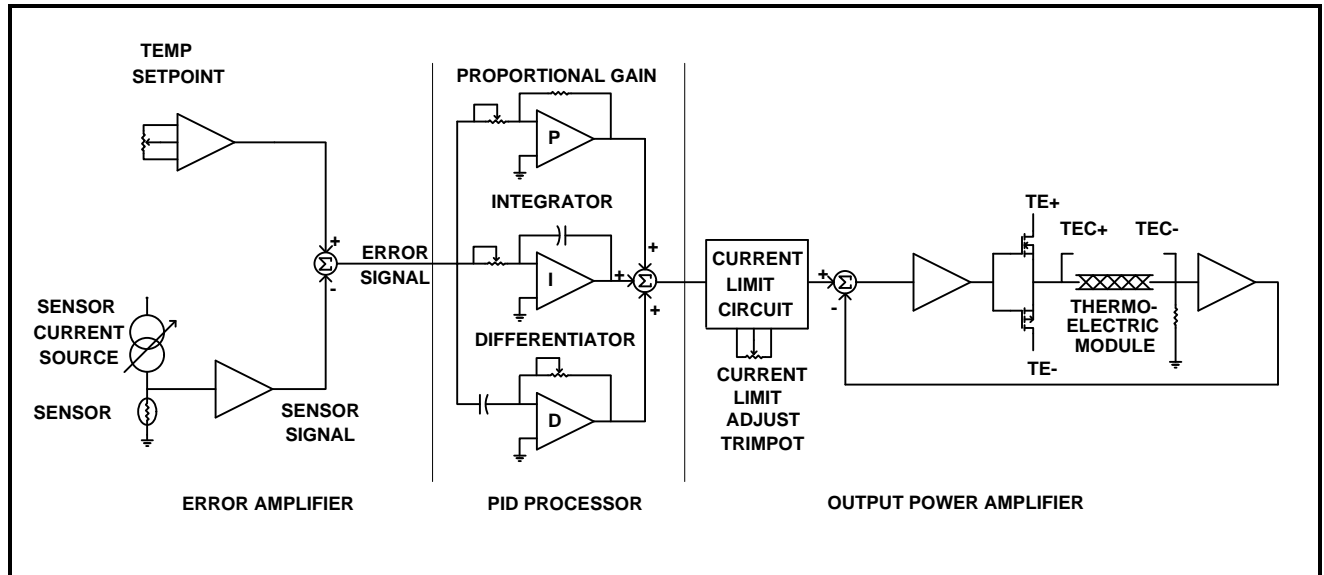
ERROR AMPLIFIER: The error amplifier section provides the difference between the setpoint temperature and the actual temperature of the load device as sensed by the temperature sensor. This difference is known as the error term. This error term is fed to the PID processor. The range of the setpoint temperature signal and the gain of the temperature sensor amplifier typically determines the temperature range of the controller for a given sensor.

The sensitivity of the error amplifier is determined by the temperature sensor amplifier gain and the sensitivity of the temperature sensor. For example, the error terms generated when using a 10kΩ thermistor and an AD590 at 15°C are quite different. With a thermistor current source of 100µA, the thermistor will produce a 76 mV/°C variation on the error term. The AD590 with a 10kΩ sense resistor will change the error term by 10 mV/°C. The AD590 will allow you to operate over a wider temperature range than the thermistor, but the thermistor will be more sensitive to temperature changes.

PID PROCESSOR: The PID processor section consists of a proportional gain amplifier, an integrator, and a differentiator, all of which can be implemented using simple op-amp circuits. In most PID controllers, the integrator time constant (I) and differentiator time constant (D) are fixed and only the proportional gain is variable. Often, (D) is not even used, even though it is necessary for an optimal system.

Simpler control loops utilize only the proportional gain stage. Proportional controllers are inherently stable for low gains, but cannot produce a zero error between the temperature setpoint and sensor feedback. A non-zero error must be maintained to produce a finite output control signal. The addition of the integrator function reduces the error to zero, but also reduces the stability of the control loop. The integrator produces a finite output even when the error term is zero because the output of the integrator is a function of past errors. Past errors charge up the integrator to some value that will remain, even if the error becomes zero. The addition of the derivative term increases stability of the loop by increasing the dampening coefficient (decreasing the decay ratio). Since the addition of the integral term usually results in larger overshoots due to integrator windup, PI or PID controllers with adaptive control loops or anti-windup circuitry are preferable.

The PID controller loop stability (dynamic response) is determined by the P, I, and D settings.   In general, increasing the proportional gain (P) and decreasing the integral time constant (I) reduces errors, but increasing the integrator time constant and differential time constant (D) increases loop stability.

OUTPUT POWER AMPLIFIER: Most thermoelectric temperature controllers use a Linear Bipolar Current Source output stage. This allows the controllers to take full advantage of the TECs capability to heat and cool. To reduce cost, a unipolar output stage can be used if the ambient environment conditions are well defined and the temperature setpoint is sufficiently lower or higher than ambient. The output power stage can be a linear voltage source but still should provide some sort of current limit to protect the TEC.

SENSOR SELECTION

The temperature sensor must provide an appropriate electrical signal to the controller. Selection should be based on at least four parameters: linearity, temperature range, sensitivity, and physical size. The requirements of the application will drive the choice of sensor.

The most common precision sensor is the negative temperature coefficient (NTC) thermistor. Other temperature sensors include platinum and copper RTDs (Resistance Temperature Detectors), and integrated circuit sensors such as the LM335 from National Semiconductor and the AD592 from Analog Devices. These are Positive Temperature Coefficient (PTC) sensors. Table 1 rates these sensors relatively.

Sensor Type	Linearity	Range	Sensitivity	Size
Thermistor	Poor	-80 to +150°C	Best	Best
RTD	Good	-260 to +850°C	Poor	Good
LM335	Best	-40 to +100°C	Good	Poor
AD592	Best	-25 to +105°C	Good	Poor

Thermistors The popularity of thermistors is mainly due to their sensitivity and size. Thermistors change several hundreds of ohms per degree Celsius. Most thermistor beads are the size of pin heads, allowing them to be precisely mounted to the device being cooled. The resistance of a thermistor decreases nonlinearly with increasing temperature, however. This property and the narrow temperature sensing range (typically 50°C maximum) are limitations for this sensor. The temperature-resistance relationship can be approximated using the Steinhart-Hart equation.

$$\frac{1}{T} = A + B\ln(R) + C[\ln(R)]^3$$

T is in Kelvin, R is in ohms, and A, B, and C are Steinhart-Hart constants specific to the thermistor. This equation will provide a ±0.01°C accuracy throughout the thermistor's temperature range. These sensors can be used in systems requiring stabilities greater than 0.005°C. For the most part, though, thermistors are suitable for fixed point systems where they repeatedly go from ambient to one fixed temperature.

RTDs Unlike thermistors, the resistance of an RTD increases linearly with temperature. Because RTDs only change fractions of an ohm per °C, they are only suitable in designs requiring no better than 0.05°C stabilities. RTDs do become nonlinear towards their range limits. Typical accuracies for a 100Ω platinum RTD are ±1.3°C at the range limits, and ±0.5°C within the mid range.

Linear Integrated Circuit Sensors The LM335 and AD592 integrated circuit sensors provide excellent linearity over their operating ranges. These sensors are three terminal devices available in TO-92 (plastic package) or TO-46 (metal can package). The LM335 changes 10 mV for every degree Kelvin. This sensor will have a 2.88 V output at room temperature (25°C) and a maximum typical error of 4°C and a 0.3°C nonlinearity over the range of operation. The AD592 provides a current output of 1μA per degree Kelvin. Error over the sensor range is 2°C and they are linear to 0.25°C. If this sensor current is applied to a 10kΩ resistor it provides a 10mV/°C transfer function similar to the LM335. These devices are suitable in designs where stabilities no better than 0.01°C are required, but a wide range of temperature will be measured.

INTEGRATING COMPONENTS

The most critical aspect of system design, once the components are chosen, is the mechanical assembly. If the heat sink is not sufficient, or thermal conduction between components is poor, the system may not only be unstable but also has the potential to damage components.

Heat sink Selection Only natural convection heat sinks will be considered in this section. The heat sink absorbs the power pumped from the TEC cold surface and heat generated by the TEC itself. Heat sink performance affects the maximum temperature range of the system and temperature stability. Many times, heat sinks are large blocks of aluminum or copper. Although these are capable of absorbing large amounts of power, once the block has heated to temperature, it does not efficiently dissipate its energy to the ambient environment. Good heat sink design includes finned extrusions for efficient heat transfer. The more surface area, the better the heat dissipation. If a heat sink is underdesigned for its application, the system may go into a condition called thermal runaway. When the TEC heat sink cannot dissipate the power being pumped to it fast enough, the temperature of the cold face increases. Sensing this rise, the controller will increase its output current to compensate. Increased current pumps more power into the heat sink, further heating the TEC cold face. This vicious cycle continues until the controller reaches its current limit. The load is no longer controlled and can not be maintained at the desired temperature.

The heat sink should be able to dissipate the power generated by the device and cooling plate, Q_C, and the power generated by the TEC (Q_{TEC}). A conservative estimate of $Q_{heatsink}$ can be calculated as follows:

$$Q_{heatsink} = Q_C + Q_{TEC} = Q_C + I_{max}V_{max}$$

where I_{max} is the TEC input current resulting in the greatest ΔT (Amps), and V_{max} is the voltage at ΔT (Volts). This allows for the fact that much more power is dissipated in reaching the desired temperature than maintaining it.

Using the value of T_H used for TEC selection, the heat sink capacity can be selected. For best results, select the heat sink with the minimum thermal resistance (TR) to maintain the TEC hot plate temperature below T_H. The thermal resistance for a heat sink is defined as its rise in temperature for every Watt of power absorbed.   The thermal resistance can be calculated as:

$$TR = \frac{(T_H - T_{ambient})}{Q_{heatsink}}$$

Mounting for Good Thermal Conduction The TEC module can be mounted to the heat sink with one of three methods: Thermal Epoxy, Compression Mounting, or Solder Mounting. The TEC manufacturer can recommend proper mounting for specific modules. If its dimensions exceed 3/4" on a side, the mechanical stress caused by the different thermal expansion rates of the TEC and heat sink tend to break the TEC's ceramic plate. Compression mounting is the only suitable mounting method for larger TEC's. Thermal grease is not rigid and allows both surfaces to move independently of each other. If the load is to be hermetically sealed, the solder method should be used since most thermal epoxies and heat sink compounds outgas in a vacuum. When mounting with heat sink compound, a thin layer, enough to fill in any air gaps, is necessary. Rotate the TEC back and forth, squeezing out any excess heat sink compound. Do not compress the TEC with more than 150 pounds of torque per square inch of TEC area. A "snug" fit is sufficient. When soldering the TEC to the heat sink, be careful not to exceed the maximum temperature to the TEC module (typically 136°C). If the soldering temperature exceeds the melting temperature of the solder used to mount the thermocouple junctions, the TEC may fall apart.

The device being cooled can be directly mounted to the TEC or a cooling plate can be used for mounting. When installing a cooling plate, limit its mass and the distance between the device being cooled and the TEC. This will facilitate faster settling times and more stable operation. The sensor should be located as close to the cooled device as possible, to improve accuracy and stability.

Thermally Isolating the Load Greater temperature stability can be achieved by reducing the effects of passive heat loads. Insulating the load with closed cell foam insulation or hermetically sealing the device chamber are two ways of reducing radiation and convection losses. Gaps between the heat sink and cooling plate should also be insulated. Very little can be done to reduce active heat load variations. In systems requiring the device to control below the dew point, a dry gas, such as N_2, needs to be added to the chamber to reduce condensation.

OPTIMIZING THE PID CONTROLLER

Once the thermoelectric cooler system is assembled, it is important to optimize the controller to the load. Optimizing a PID controller will reduce overshoot and settling time and improve temperature stability.

If the PID loop is significantly underdamped, it will overreact to transient load and ambient environment variations. This can be visualized best when considering a temperature controlled laser diode being pulsed on and off. With each pulse, heat is generated quickly. An underdamped system will respond too quickly and cycle around the setpoint. When the PID loop is significantly overdamped, it will sluggishly respond to transient and ambient environment variations. In either case, the short term temperature stability of the laser diode will be poor.

FIGURE 2 shows the response of a simple PID controller stabilizing a load at 15°C from an ambient temperature of 21°C. Several important optimizing factors can be determined from this response. Note this graph was taken using computerized data acquisition, but the following measurements can be taken manually also. We are trying to find the rate of change in temperature vs. time (R), how far the load overshoots the desired temperature ($T_{overshoot}$), decay temperature (T_{decay}), and the time it takes the load to settle (t_{settle}).
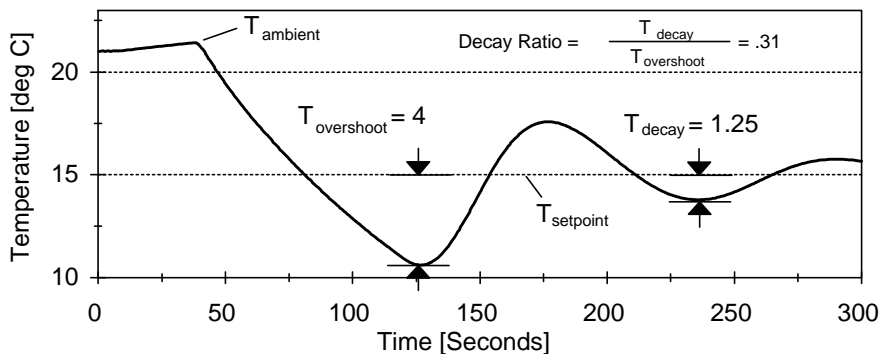

FIGURE 2. Proportional, integral and differential (PID) controller attempts to stabilize load at a 15°C setpoint temperature.

R can be approximated by measuring the time it takes to vary the load from $T_{ambient}$ until it first gets to $T_{setpoint}$. In this graph it is (15°C-21°C) / (87sec - 40sec) or -0.071°C/sec. If R is too small, the system may respond too slowly to ambient changes. If R is too large, the controller may overreact to changes in the load and become unstable.

The overshoot temperature is the difference between the desired temperature, and the maximum deviation of temperature from ambient. In Figure 2, this is 4°C. The decay temperature is measured after the load crosses back over the setpoint and overshoots again. In Figure 2, this is 1.25°C. From the values of T_{decay} and $T_{overshoot}$, we can determine the decay ratio (dampening) of the system and the loop stability.

Settling time is how long the system requires to stabilize to a steady-state temperature. Try to minimize this, but tradeoffs between settling time and stability must be made when optimizing the system.

Set Controller Current Limit   The first and most important step in setting up the controller is to set the current limit near I_{max} of the TEC. Secondly, and just as important, is to know the temperature range of the device being cooled. If the device can be damaged by extreme cold or heat, precautions should be taken to limit the controller's temperature range.

Set Initial P, I, and D Terms   From the "PID Controllers Explained" section we know the longer the integrator time constant (I), the less chance of instability. It is therefore best to initially set this term as large as possible. Many controllers fix this term, so it may not be accessible. Next, the proportional gain should be set in the middle of gain range. Too large or too small a gain will make most loads cycle. If the differentiator time constant (D) is adjustable, set this term to its largest value to increase loop stability.

Figure 3 shows the response of a thermal system when the proportional gain is varied and (I) is held constant and when the integrator time constant is varied and the proportional gain is held constant. Overshoot is largest for the smallest value of P. Note that systems with low gain values do not settle quickly, and appear to cycle around the setpoint. Large proportional gains dampen the system, but increase the settling time. The lowest integrator time constant produces the least overshoot, but also causes short term cycling. As (I) increases, however, the settling time increases. An optimized PID loop should produce a response between the middle curves, overshoot balanced with a reasonably fast settling time.

FIGURE 3. Trade-offs arise when optimizing variables such as proportional gain and integral time constant. Holding integral time constant at 1 s and varying the gain for 10 to 50 increases the system's damping coefficient (A); keeping proportional gain at 30 and varying the integral time constant from 0.2 to 0.8 s increases the overshoot (B).
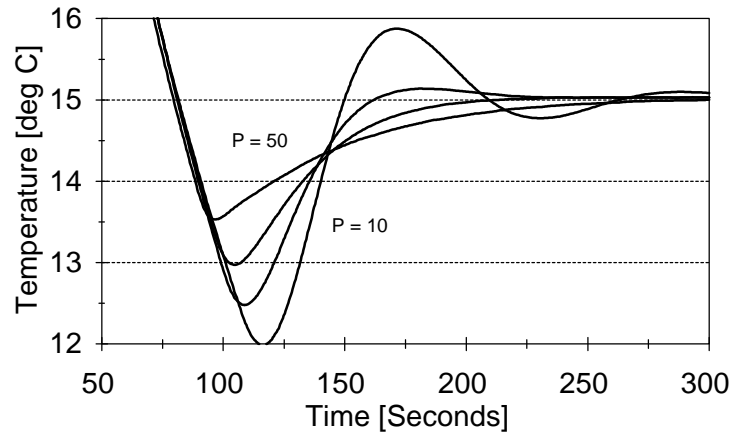
A) Integral Time Constant (I) held at 1 second.
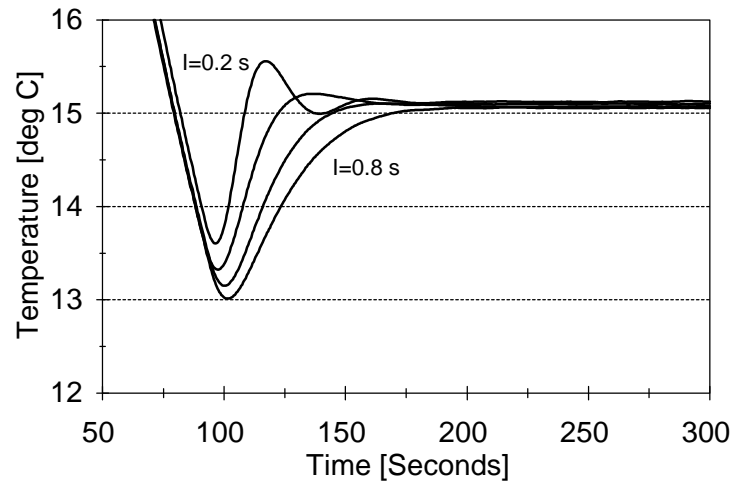
B) Proportional Gain (P) held constant at 30.

Set Decay Ratio For expedience, optimize at a setpoint halfway between ambient and the desired load temperature. If the system is properly optimized, the performance will be similar throughout the range of operation.

The decay ratio is a measure of system stability; the larger the decay ratio, the poorer the system loop stability. A decay ratio value greater than 0.25 means the system is greatly underdamped and is susceptible to cycling or instability. For example, the system in Figure 2 has a decay ratio of (1.25/4) or 0.31. The system also cycles around the setpoint and is underdamped. The decay ratio is calculated with:

$$\text{Decay Ratio} = \frac{T_{decay}}{T_{overshoot}}$$

If your system's decay ratio exceeds 0.25, increase the proportional gain until it drops below 0.25.   The closer this value approaches zero, the more damped the control loop. For thermal systems, try to obtain a decay ratio between zero and 0.1 for optimal performance. This provides a slightly underdamped system.

When the I and D terms can be adjusted, the system can be further optimized. Adjust the proportional gain until the decay ratio is less than 0.025. Decrease the integrator time constant until the decay ratio increases to 0.05. Set the D term to one-quarter of the Integrator time constant.

Now that the system is tuned for the mid-range of operation, check the extreme temperature operation to ensure the overshoot and settling time are satisfactory. Figure 4 shows an optimized system's response at different setpoints. Performance is similar in all four.
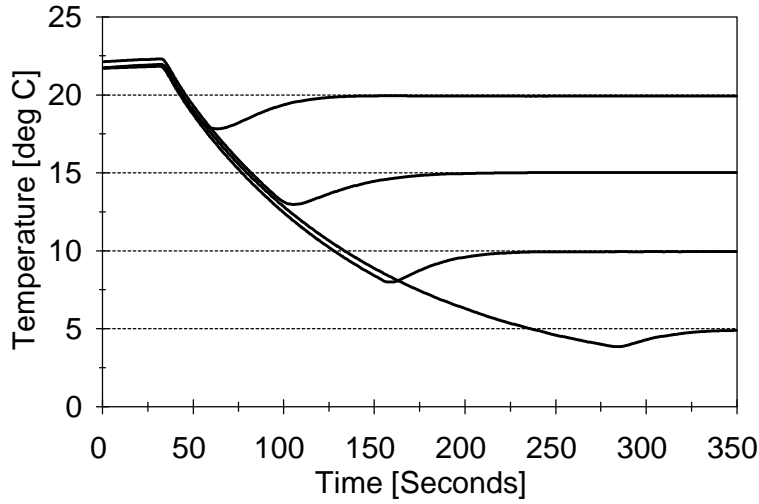

FIGURE 4. Optimized system settles at different temperature setpoints (proportional term is 30 and integral time constant is 1 s).

If your system does not reach the setpoint, the current limit might be set too low or the controller's compliance voltage may be limiting the output current (Fig. 5). Once this controller achieved temperature stability at 16°C, its output current settled around 400 mA. Notice from the graph that the lowest current limit setting of 500mA settles very, very slowly, even though the current exceeds the necessary steady state current. This effect can be used to limit the temperature overshoot of the setpoint at the sacrifice of increased settling time.
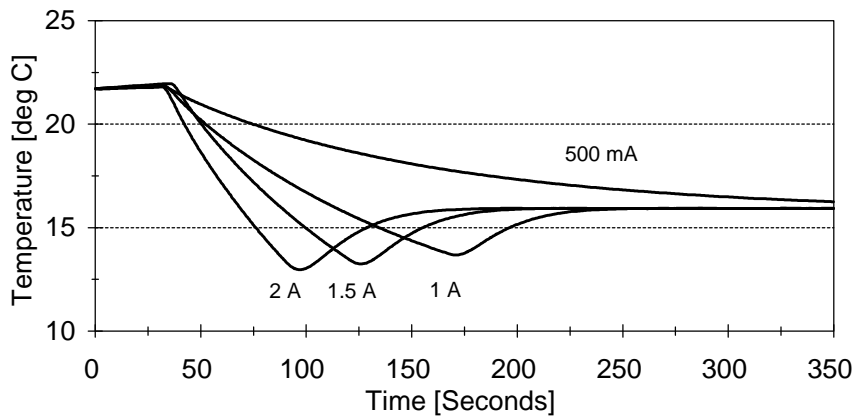

Figure 5. Even though the steady-state operating current is 400 mA, the current limit should be set near I_{max} of the TEC for the best settling time.

TROUBLESHOOTING

Because the rules given here are general rules of thumb, some tweaking may be necessary to account for special load circumstances. The following list details common problems, their definitions, and suggestions for solving them.

CYCLING - The load temperature varies repetitively around the setpoint without settling at a stable temperature.

- The sensor may have a poor thermal bond to the load. When the sensor is not firmly attached to the load a thermal time delay will exist. The controller is responding to a delayed error signal that may not be representative of existing conditions. Bond the sensor to the load with thermal epoxy, or at least fill in any air gaps with thermal grease. If the sensor doesn't fit snugly in its mounting hole, the extra epoxy required to hold it may also induce a thermal lag.
- The sensor may be too far from the TEC, or the thermal mass of the TEC and cooling plate may be too large. Either problem causes a thermal time delay. This can be solved by moving the sensor closer to the TEC, reducing the mass of the cooling plate, or increasing the heat pumping capability of the system by using a larger TEC or a controller with greater power capacity.
- The current limit may be set too low. The system will respond slowly to the controller output, so the controller will overcorrect for temperature variations. If the current limit must be set low due to power restrictions, then the integrator time constant must be increased.

LARGE OVERSHOOT - When first cooling, the temperature will drop below the setpoint. Large overshoot is a problem if the device being cooled can be damaged by too low a temperature.

- Increase the proportional gain or decrease the integrator time constant (see Optimizing the PID Controller p. 8).
- Reduce the sensor time delay. Either reduce the thermal mass in the cooling plate or provide a shorter thermal path between the temperature sensor and load.
- Poor thermal bond to sensor.
- Sensitivity of sensor is too low. Either choose a sensor with better resolution or increase the sensor signal.

LONG SETTLING TIME - The settling time is very dependent on the load configuration. If the load temperature crosses the setpoint more than twice before settling, it may be underdamped. If the load doesn't cross the setpoint after overshooting, it may be overdamped.

- If the system is underdamped, increase the integrator time constant.
- If the system is overdamped, reduce the proportional gain.

POOR TEMPERATURE STABILITY - Non-cyclical variations around the setpoint occur.

- The load may be exposed to large ambient temperature fluctuations. If possible, isolate the load with closed cell foam or hermetically seal the assembly.
- When the sensor is a long distance from the device being cooled or not properly thermally connected, the sensor will not accurately track its temperature. Reposition the sensor, and insure a good thermal bond.
- If the TEC is not flat against the heat sink or cooling plate, or thermal grease or epoxy does not completely fill air gaps, then the TEC module can lift and swell, changing the heat pumping capacity as the surface area connected to the heat sink varies.

THERMAL RUNAWAY - The heat produced by the TEC and load is not removed quickly enough. The sensor detects increased temperature and the cooling current through the TEC is increased, causing more power to be dissipated by the TEC, further increasing the temperature.

- This can be caused by insufficient TEC heat sinking. Select a heat sink with a lower thermal resistance or force air across the heat sink.
- The current limit may be set higher than the TEC can handle. If too much current flows through the module, it can overheat, possibly melting the solder joints and damaging the TEC.
- If the ambient temperature is too high, the heat sink capacity is reduced. Either increase the capacity of the heat sink or consider forcing airflow across it.

NOISE ON THE LOAD - Many temperature controlled devices are electronic components capable of picking up electrical noise. Since the sensor and TEC are typically located near the load, they can radiate noise onto the device being cooled. Ferrite beads and filter capacitors can be added to the thermistor and TEC leads to minimize radiation effects, and shielded cables should be used.

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