Application Note AN-TC09 Rev. B

Specifying Thermoelectric Coolers

October, 2015

INTRODUCTION

Thermoelectric coolers (TECs) are commonly used in applications requiring extremely stable temperature control across a wide range of operating and ambient conditions.

TECs are solid state devices: they are relatively easy to use, highly reliable, and rugged when properly installed. Since they are all-electronic devices, they can be controlled with high repeatability for precise and predictable performance. Driving current through the TEC causes it to pump heat from one side to the other, which creates a Cold Side and a Hot Side. Reversing the direction of the current flow reverses the heat pump direction.

Laser diode systems that require narrow linewidths combine low noise laser current sources with high performance temperature control to achieve the required stability. Example applications include cancer treatments, spectroscopy, telecommunications, and trace chemical detection systems. Detector systems approaching the noise floor also use precision temperature control to increase responsivity and reduce noise. TEC based biological sample coolers replace refrigerators that use environmentally harmful chemical coolants. **Figure 1** illustrates a simple system layout.

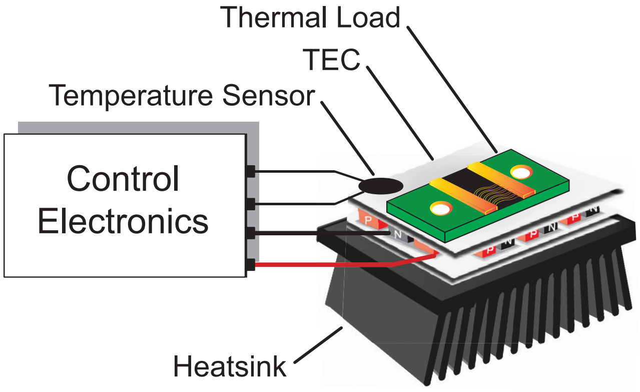

Figure 1. Basic System Components

This Application Note provides practical tools for selecting the thermoelectric cooler for your system. The goal is to design a system that maintains the required load temperature, has sufficient overhead to handle short excursions from anticipated environmental conditions, and is safe from thermal runaway.

SYSTEM COMPONENTS

Fundamentally, TECs are heat pumps—they pump heat from one side to the other, and the heat pump direction is determined by the direction of current flow through the TEC.

Normally a heat-generating load, such as a laser diode, is placed on the Cold Side. The TEC pumps away the waste heat in order to keep the laser diode at the required operating temperature.

The Hot Side must be properly heatsinked in order to dissipate the heat pumped from the Cold Side. And since nothing is free in thermodynamics, the TEC generates heat that must also be dissipated by the heatsink.

From this simplified description, the building blocks of the TEC control system can be identified.

Thermoelectric Cooler (TEC)

- The TEC must have sufficient heat pump capacity to move the heat away from the active load on the Cold Side of the TEC, to the heatsink on the Hot Side, where the waste heat is dissipated to ambient.
- The TEC must be selected to fit within the physical size constraints of the system.
- The TEC must be selected in conjunction with the controller to guarantee that the controller has sufficient current and voltage overhead.

Temperature / TEC Controller

- The temperature controller must be able to deliver the drive current required by the TEC, as well as have sufficient compliance voltage.
- The controller must have adequate control resolution and stability for the application requirements.
- Certain features make the controller more usable in a wide range of applications. PID loop tuning, output current and voltage limits, a default safe-temperature setting, and other such functions may not be absolutely necessary but will make the system far more robust and enhance long-term reliability.

Heatsink

The heatsink must be adequately sized to dissipate the heat generated by the thermal load, plus the heat generated by the TEC. The ambient temperature also plays a role in selecting the heatsink. Generally, heatsinks with high thermal conductivity are desirable, but other design considerations must be taken into account. The size of the enclosure, venting, anticipated airflow, cost, and environmental exposure all play a role in choosing the most effective heatsink.

Heatsink design is beyond the scope of this Application Note, but the information presented here will help to define the minimum thermal conductivity of the heatsink for your application.

Temperature Sensor

The temperature sensor must have sufficient range and resolution for the application:

- RTDs operate over a wide temperature range and have a linear resistance response to temperature, but are not the most accurate or sensitive choice.
- The active semiconductor sensors (AD590, LM335, etc) also operate over a wide range, respond linearly, and are typically more accurate than RTDs.
- Thermistors, when selected properly, offer the best accuracy and repeatability. Thermistors do not respond linearly to temperature, and this characteristic can be used to greatly increase control resolution and accuracy around the target setpoint.

DESIGN OVERHEAD

One important aspect of thermal system design is building in sufficient “overhead,” or excess thermal control capacity.

Temperature control systems are designed to work at nominal environmental and operational parameters, such as ambient temperature and laser output power. There may be times when the system has to operate outside of those parameters but must continue to be reliable and safe. A particularly hot day in the desert, for example, will reduce heatsink efficiency and may make the system susceptible to thermal runaway.

Designing in sufficient overhead will allow the system to operate through anomalous conditions without damaging sensitive components.

CALCULATE THE TOTAL THERMOELECTRIC HEAT LOAD

Several parameters must be known before the TEC selection process can begin. The first step is defining the total thermal load, Q_{TOTAL}, on the TEC, per **Eq 1.**

EQ 1. Total Thermal Load

$$Q_{TOTAL} = Q_{RADIATED} + Q_{CONVECTIVE} + Q_{CONDUCTED} + Q_{ACTIVE}$$

$\mathbf{Q_{RADIATED}}$ is the heat radiated from the thermal load to the ambient environment. Within a laser diode package, $Q_{RADIATED}$ is typically insignificant.

EQ 2. Heat Radiated from Thermal Load

$$Q_{RADIATED} = F\,\varepsilon\,\sigma\,A\,(T_{AMB}{}^{4} - T_{C}{}^{4})$$

$\mathbf{Q_{CONVECTIVE}}$ is the heat conducted away from the thermal load to the ambient environment by air currents. In a laser diode package the convective heat loss from the load is usually negligible.

EQ 3. Heat Conducted Away by Air Currents

$$Q_{CONVECTIVE} = h\,A\,(T_{AMB} - T_{C})$$

$\mathbf{Q_{CONDUCTED}}$ is the heat that is conducted from the thermal load by physical connections such as wires and clamps.

EQ 4. Heat Conducted Away by Physical Connection

$$Q_{CONDUCTED} = k\,W\,/\,(T_{AMB} - T_{C})$$

$\mathbf{Q_{ACTIVE}}$ is the heat generated by the thermal load.

EQ 5. Heat Generated by Thermal Load

$$Q_{ACTIVE} = V_{L} * I_{L} - P_{OPTICAL}$$

F = shape factor; assume worst-case value of 1
ε = emissivity; assume a worst-case value of 1
σ = Stefan-Boltzman constant (5.667×10^{-8} W/m^{2}K^2)
A = area of cooled surface (m^2)
h = convective heat transfer coefficient (air 21.7 W/m^{2}ºC)
k = thermal conductivity of the wire (copper is 386 W/mºC)
W = cross-section area of the wire (m^2)
T_{AMB} = ambient air temperature around heat load (K)
T_{C} = temperature of cooled heat load (K)
V_{L} = load forward voltage (V_{F} in volts)
I_{L} = load forward current (I_{F} in amps)
$P_{OPTICAL}$ = optical output power (W)

Example Case

Consider a small telecommunications laser diode, perhaps 100 mW output power with a forward voltage of 2.55 V and current of 1.8 A. With these basic laser diode parameters, use Equation 5 to calculate $Q_{ACTIVE} = 2.55 * 1.8 - 0.1 = 4.5$ W.

If the laser diode is mounted to a small aluminum plate, about 1/4” x 1/2” x 1/16”, then $Q_{RADIATED} = 5.67 \times 10^{-5}$ W.

In a small confined environment of a laser diode package, or other application where there is little or no airflow over the laser diode, $Q_{CONVECTIVE} = 1.38 \times 10^{-5}$ W.

Assuming small diameter copper wire to connect to the laser diode, $Q_{CONDUCTED} = 0.0015$ W.

Summing these terms, $Q_{TOTAL} = 4.5$ W. This example demonstrates that $Q_{RADIATED}$, $Q_{CONVECTIVE}$, and $Q_{CONDUCTED}$ are sometimes small enough that they can be ignored.

The total thermoelectric heat load is one of the parameters needed to select the right TEC for the application. In this case the heat pump capacity of the TEC, usually called Q_{MAX}, must be at least 4.5 W.

SELECT THE TEC AND CONTROLLER

TECs are readily available from a number of manufacturers, and come in a range of physical and electrical configurations. Prototyping a system can usually be done with an off-the-shelf TEC, and most manufacturers are able to build custom TECs to suit unique applications.

First, for a robust design, we recommend that you select a TEC that has a Q_{MAX} specification at least two-times greater than Q_{TOTAL} calculated above. It is critical that the TEC have this excess heat-pump capacity in order to avoid a dangerous condition called *Thermal Runaway*. Thermal runaway is discussed on page 5.

Simultaneously, begin reviewing the specifications for TEC controllers that will suit your application. Different controllers are appropriate for different situations: a benchtop test instrument, for example, will not be useful in applications where the final product is an OEM enclosure containing an integrated laser control system.

OEM-specific controllers can be used for benchtop use if the manufacturer has made an evaluation board. If the eventual application is an OEM product, prototyping should be done with the same controller that will be used in the end product. Doing so will save time and money down the road, and there will be no surprises when it's time to transition from prototype-to-beta-to-production.

It is important to select a controller with adequate safety features. A user-adjustable output current limit prevents over-driving and destroying the TEC. An adjustable output voltage limit adds another layer of protection.

The electrical specifications of the TEC must fit within the capabilities of the controller, and with some overhead so that the controller is not operating at its maximum capacity during normal foreseeable conditions.

In addition to selecting a controller with sufficient current to drive the TEC, make sure the controller output voltage is sufficient. If the controller reaches its maximum output voltage, the controller is said to be "compliance limited" and it will not be able to adequately drive the TEC.

Other important controller features that increase the functionality of the system include:

- Temperature sensor compatibility: if the application uses a thermistor or RTD, the controller should be able to bias the sensor with a stable and precise current. Since different sensor types require different bias currents, a controller with selectable bias current range works in a wider variety of application environments and offers greater flexibility for prototyping.

- Monitor Outputs: An OEM controller with signal monitor outputs can be integrated into a comprehensive control system. Actual Temperature, Temperature In-Range, Setpoint Monitors, and other signals allow a complete control system to be built around the OEM controller.

- Integrated Laser Diode Control: A full-featured OEM temperature controller can also be integrated with a similarly-featured OEM laser diode driver, building a system that maximizes laser diode protection and usability.

VALIDATE THE TEC SELECTION

Once the TEC is selected, the design can be validated using a fairly simple equation. This equation calculates the steady-state load temperature at the specified operating and design conditions (see **Eq 6**). By graphing T_{LOAD} vs. TEC current, the system performance can be determined over a wide range of operating conditions.

EQ 6. Steady-State Load Temperature

$$T_{LOAD} = T_{AMBIENT} + T_{LOAD\_INCREASE} + T_{LOAD\_DECREASE}{}^{1}$$

$T_{AMBIENT}$ is the ambient temperature. The ambient is represented in the equation because the entire system would stabilize to $T_{AMBIENT}$ if the controller was switched off.

$T_{LOAD\_INCREASE}$ represents the increase in load temperature due to the power consumption of the load plus the power consumption of the TEC; see **Eq 7**.

EQ 7. Load Temperature Increase

$$T_{LOAD\_INCREASE} = \frac{Q_{LOAD} + I_{TEC}{}^{2} * R_{P}}{C_{HEATSINK}}$$

$T_{LOAD\_DECREASE}$ is the temperature decrease due to heat being pumped away from the load by the TEC; see **Eq 8**.

EQ 8. Load Temperature Decrease

$$T_{LOAD\_DECREASE} = \frac{-P * I_{TEC} + (I_{TEC}{}^{2} * R_{P})/2 + Q_{LOAD}}{C_{LOAD\text{-}AMB} + C_{TEC}}$$

The variables are defined as follows. Refer to the TEC datasheet for I_{TEC}, V_{MAX}, I_{MAX}, Q_{MAX}, and dT_{MAX}.

T_{LOAD} = Steady-state load temp. given these conditions (ºC)
$T_{AMBIENT}$ = Ambient temperature (ºC)
Q_{LOAD} = Total active thermal load (W)
I_{TEC} = Maximum TEC drive current (A)
R_{P} = Resistance of TEC at maximum power (V_{MAX} / I_{MAX}; Ω)
$C_{HEATSINK}$ = Thermal conductivity, heatsink to ambient (W / ºC)
$C_{LOAD\text{-}AMB}$ = Thermal conductivity of load to ambient (W / ºC)
C_{TEC} = Thermal conductivity of TEC (Q_{MAX} / dT_{MAX}; W / ºC)

P = Peltier Coefficient; an approximate measure of the ability of the TEC to pump heat. See **Eq 9**.

EQ 9. Peltier Coefficient

$$P = \frac{Q_{MAX} + I_{MAX}{}^{2} * R_{P}/2}{I_{MAX}}$$

Consider the following example, which illustrates several important design issues.

The design goal is to maintain a laser at 20ºC while it dissipates 4.5 W. The ambient temperature is 45ºC, a hot environment. The heatsink thermal conductivity is 1.57 W / ºC. The TEC has these characteristics (from the TEC datasheet):

dT_{MAX} = 70ºC	I_{MAX} = 2.3 A
Q_{MAX} = 11.4 W	V_{MAX} = 7.9 V

Eq 6 can be used to generate a graph of load temperature vs. TEC current in order to determine if the TEC has sufficient heat pump capacity to maintain the load at the required temperature. The resulting T_{LOAD} vs. I_{TEC} graph is shown in **Figure 2**.

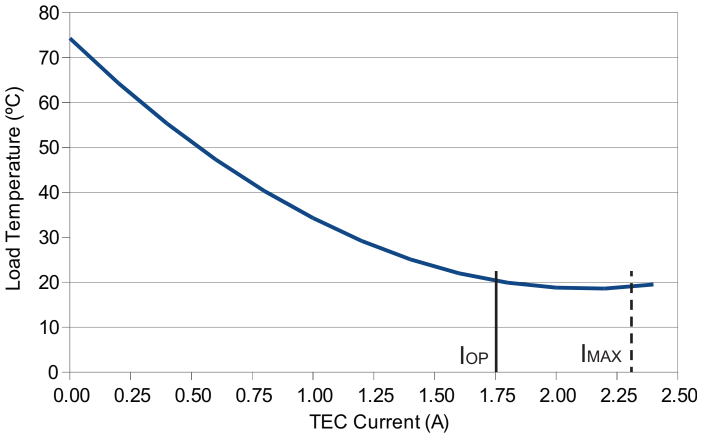

Figure 2. T_{LOAD} **vs.** I_{TEC}

Figure 2 contains a wealth of information about the expected performance of the thermal system. First, in order to maintain the load at 20ºC at the prescribed ambient conditions, the controller operating current (I_{OP}) is 1.74 A.

Other conclusions from this graph:

- By driving the TEC at 2.15 A, the minimum load temperature is about 18.5ºC.
- The TEC / controller combination specified will work for the load and ambient conditions, but the system has about 1.5ºC of temperature overhead (20ºC – 18.5ºC). If the ambient temperature increases by more than 1.5ºC, the controller will drive more than 2.15 A, and the load temperature will actually begin to increase because the thermal runaway cycle has begun.
- The current control overhead is 0.4 A. If the load heat dissipation increases beyond the expected level, the TEC has very little excess current capacity before reaching I_{TEC_MAX}.

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[1] electronic design, s.v. "Simple design equations for thermoelectric coolers" by W. Stephen Woodward, posted 23 February 1998.

THERMAL RUNAWAY

Thermal runaway is a condition that results from inadequate heat dissipation.

Consider a case where the heatsink is too small for the amount of heat it must dissipate. Since heat is being pumped into it, and it's not dissipating enough of the heat to ambient, the temperature of the heatsink continuously increases. In turn, the temperature of the TEC increases, and then the temperature of the load increases.

Sensing the increased load temperature, the controller increases the drive current to the TEC. Normally, increasing the current would cause the load temperature to decrease as the TEC pumps more heat away from the load. But in this case, the increased power consumption of the TEC adds to the amount of heat being dumped to the heatsink, and again the temperature of the thermal stack-up increases—further increasing the load temperature.

This cycle continues until the controller reaches the drive current limit, and some part of the system finally fails.

This failure mode is more likely when the heatsink is just adequate for the nominal design conditions, but an unexpectedly high ambient temperature reduces the efficacy of the heatsink.

Proper system design with sufficient temperature and current control overhead will prevent thermal runaway.

PREDICT THERMAL RUNAWAY

Notice that the curve in **Figure 2** changes direction at about 2.15 A; this current is called I_{TEC_MAX}. If the controller drives more than 2.15 A, the heatsink will not be able to dissipate all the heat to the ambient environment, and the thermal runaway cycle will begin.

I_{TEC_MAX} can be calculated using the values from the TEC validation section above, and **Eq 10**.

EQ 10. Calculating I_{TEC_MAX}

$$I_{TEC\_MAX} = \frac{P * C_{HEATSINK}}{R_P * (C_{HEATSINK} + 2 * (C_{LOAD\_AMB} + C_{TEC}))}$$

Operating the controller for an extended period of time at I_{TEC_MAX} will result in thermal runaway, so the drive current limit should be set to the I_{TEC_MAX} value, or slightly lower.

In order to make sure the full performance is realized from the TEC and controller, but still maintain the system within a safe operating range, it's important to design in overhead whenever possible:

- Over-size the heatsink, or add a fan to force air flow and increase heatsink efficacy.
- Choose a TEC with greater-than-required heat pump capacity.
- Design the system so that I_{OP} is well below I_{TEC_MAX}

Even in cases where the initial design does not seem prone to thermal runaway, it is wise to select a different TEC or heatsink and repeat the validation process. Using different components may result in unanticipated performance benefits.

The next two design examples illustrate the effects of changing components in order to broaden the environmental conditions that the system can tolerate.

DESIGN ITERATION: LARGER HEATSINK

The configuration outlined above is sufficient to operate under the design conditions, but just barely. **Figure 3** illustrates that there is very little design overhead, both in terms of temperature and TEC current.

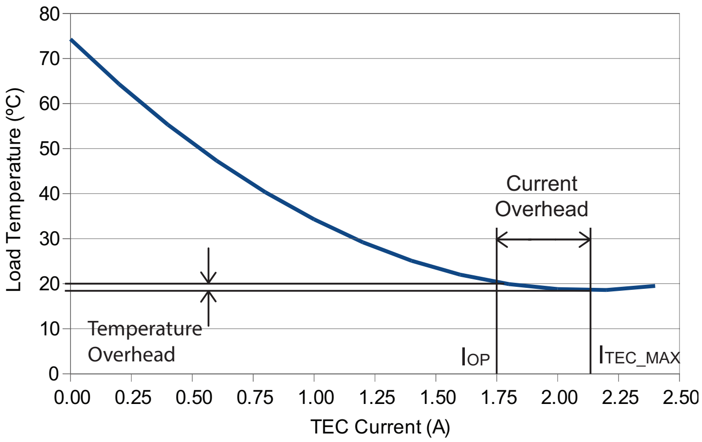

Figure 3. Design Overhead

The temperature overhead is 1.5ºC, meaning this design can tolerate an ambient temperature increase of only 1.5ºC before the controller drives to I_{TEC_MAX}. Likewise, the current overhead is small—only 0.4 A. If the load heat dissipation should increase slightly, the controller will be forced to drive the TEC at or near I_{TEC_MAX}. in order to maintain the design temperature of 20ºC.

Using a heatsink with a higher thermal conductivity dramatically improves system performance. **Figure 4** compares the performance of the original heatsink and a heatsink with thermal conductivity of 2 W / ºC.

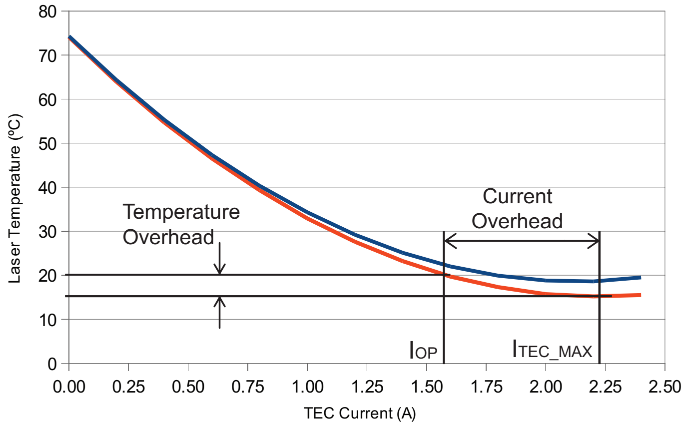

Figure 4. Design Iteration, More Efficient Heatsink

These operating points have changed:

- I_{OP}: decreases from 1.75 A to 1.58 A
- Temperature overhead increases from 1.5ºC to 4.8ºC
- Current overhead increases from 0.4 A to 0.64 A

DESIGN ITERATION: LARGER TEC

Another way to increase the design overhead is to select a TEC with greater heat pump capacity. **Figure 5** compares the performance of the original design with a system using a TEC with greater heat pump capacity.

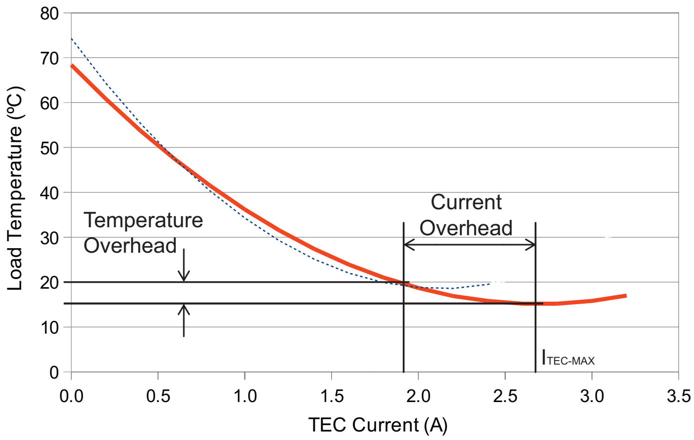

Figure 5. T_{LOAD} vs. I_{TEC}, Design Iteration

The specifications for this TEC are:

dT_{MAX} = 69ºC	I_{MAX} = 3.1 A
Q_{MAX} = 14.8 W	V_{MAX} = 7.8 V

Using this larger TEC increases the temperature overhead to 5ºC and the current overhead to 0.81 A, a substantial improvement over the first design.

With this TEC, I_{OP} = 1.88 A to maintain 20ºC, a slight increase over the 1.74 A of the first design attempt. Ultimately the system designer must decide if the additional 0.14 A steady-state current draw is an acceptable design compromise for the additional temperature and current overhead realized with this TEC.

PUTTING IT ALL TOGETHER

This Application Note is intended to help you design the thermoelectric temperature control portion of your complex system. The tools presented here provide good first-approximations for choosing system components, as well as a means for examining the effects of design changes. Using these tools will ultimately help you to save time and money while you identify the most efficient design in terms of cost, size, power consumption, and performance criteria.

Refer to other Wavelength Electronics Application and Technical notes for more information on designing and assembling temperature control systems for a wide range of applications.

KEYWORDS

Temperature controller, Thermistor, Thermoelectric, ntc thermistor, tec controllers, temperature controller, temperature controls, temperature sensor, thermistor, thermistors, thermo electric, thermo-electric, thermoelectric, thermoelectric control, thermoelectric controller, thermoelectric controllers, thermoelectric cooler, thermoelectric coolers, thermoelectric cooling, Peltier device, Peltier cooler, heat pump, thermal runaway

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