Compliance Voltage & Temperature Control Design with Multiple Thermoelectric Coolers

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ABSTRACT

Optimally using thermoelectric coolers (TECs) in conjunction with accurate sensors and adaptive controllers enables temperature stability as good as 0.9 milliKelvin. In some scenarios, multiple TECs are utilized for larger mass loads, but can also introduce additional technical challenges. This Application Note will discuss common issues when using multiple TECs, how to properly setup and simplify a multi-TEC system, and discuss the major role that the compliance voltage of the controller plays in producing a successful temperature controlled system.

CONTENTS

INTRODUCTION

Thermoelectric coolers (TECs) are solid state devices that work based on the Peltier Effect. By introducing a current, one plate of the TEC becomes hot relative to the other. A current in the opposite direction reverses the hot and cold sides.

TECs are extremely useful for precisely controlling temperatures of experimental systems. They come in a variety of sizes, with differing current/voltage capacities and maximum temperature differentials. Many of the new TECs manufactured are low impedance, requiring less compliance voltage and simplifying power supply design.

For more information about TECs, refer to Application Note *AN-TC09: Specifying Thermoelectric Coolers*.

TECs require a current supply for operation. Ideally, the current supply has safety features such as high and low temperature limits, current limits, and voltage limits. All of these things contribute to the overall safety of the equipment being used, as well as the operator.

Wavelength offers TEC Controllers that, in addition to the safety features above, are specially designed to maximize the stability of TECs. In addition to providing the power for the TEC, they are able to use signals from different temperature sensors (thermistors, resistance-temperature devices, semiconductor temperature sensors, etc.) in order to make an active feedback loop for maximum stability. Using PID control, these controllers can have stabilities as low as 0.0009°C when using a thermistor as the sensor.

For more information about TEC Controllers, refer to Application Note *AN-TC10: Temperature Controller Basics*.

COMPLIANCE VOLTAGE & SOA

There are two important design parameters to consider prior to designing any temperature control system. Neglecting either of them will result in subpar system performance, and possibly controller failure.

The first is the compliance voltage. The second is the Safe Operating Area (SOA).

The *compliance voltage* is defined as the maximum voltage the controller can deliver to the TEC at maximum current. Reaching the compliance voltage limit impacts the controller's ability to adapt to temperature changes and keep the load at a stable temperature. In depth discussion of the compliance voltage will be presented in the following sections.

The *Safe Operating Area* defines the maximum internal power dissipation allowed for the controller across a range of operating currents and power supply voltages. Note that the SOA only applies to components and modules; instruments have built-in shutdown conditions when their maximum temperature is exceeded. When controllers are operated within the SOA, the temperature of internal parts will stay in a safe, reliable zone. Operating outside the SOA can cause permanent damage to the unit and possible danger to the operator.

$V_{CONTROLLER}$ is the voltage not dropped across the TEC and must be dropped across the current controller itself. This voltage is related to internal power dissipation P via

$$P = IV_{CONTROLLER}\,, \qquad \textbf{(1)}$$

where I is the current in Amps.

The voltage drop across the TEC will follow Ohm's Law,

$$V_{TEC} = IR_{TEC}\,, \qquad \textbf{(2)}$$

where V_{TEC} is the voltage in Volts, I is the current in Amps, and R_{TEC} is the resistance in Ohms.

Let V_{PS} be the DC voltage powering the controller. Then, after the TEC, the voltage $V_{CONTROLLER}$ is

$$V_{CONTROLLER} = V_{PS} - V_{TEC}\,. \qquad \textbf{(3)}$$

Each Wavelength TEC controller has been tested to failure, and has a robust specification for its maximum internal power dissipation. To simplify SOA evaluation, Wavelength has the SOA Calculator for Temperature Controllers design tool. It has adaptable parameters for different accessories, ambient temperatures, etc. This is the simplest, most up to date method of finding whether or not the particular power supply and thermoelectric configuration will be within the Safe Operating Area for one of Wavelength's temperature controllers.

SOA EXAMPLE

In the following example, Equations (1) - (3) will be utilized to emphasize the importance of the Safe Operating Area.

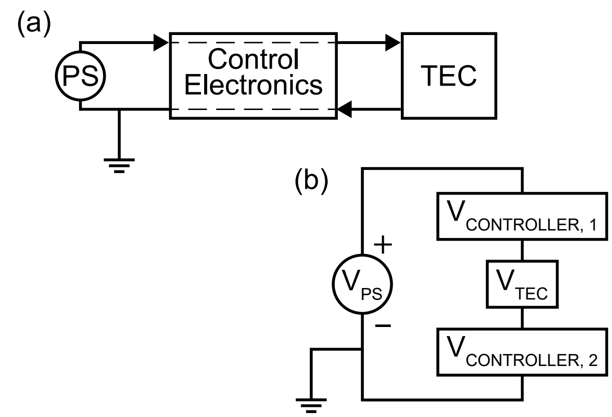

Figure 1. Upper circuit (a) shows the current flow for the SOA example. Lower circuit (b) shows the corresponding voltage drops.

Figure 1 will be the reference for the following example.

In this example, the power supply provides a voltage and a current to the control electronics. The control electronics use some voltage to power themselves ($V_{CONTROLLER,\,1}$), then give an output voltage to the TEC. There is then a voltage drop across the TEC (V_{TEC}). The control electronics are bipolar, drawing current both directions, so there is another internal voltage drop after the TEC ($V_{CONTROLLER,\,2}$).

Mathematically, the above scenario can be described by

$$V_{PS} = V_{CONTROLLER,\,1} + V_{TEC} + V_{CONTROLLER,\,2}\,. \qquad \textbf{(4)}$$

Re-writing $V_{CONTROLLER,\,1} + V_{CONTROLLER,\,2}$ as $V_{CONTROLLER}$, and rearranging, Equation (4) can be written as

$$V_{CONTROLLER} = V_{PS} - V_{TEC}\,. \qquad \textbf{(5)}$$

This means that the amount of voltage that must be dropped across the control electronics is the difference between the voltage of the power supply and the voltage drop across the TEC.

For a numerical example, consider a TEC with a resistance of 1.5Ω, and a power supply input of 25V, with a controller output current of 2A. From Equation (2), V_{TEC} is then 3V. Using Equation (5), the control electronics have to withstand 22V at 2A. In terms of power dissipated, using Equation (1), with the given current and voltage, the power dissipated in the controller is 44W. The HTC or WTC Series (9 W max) would not be good choices, but the PTC Series (60 W max) would.

Use the SOA calculator for the specific Wavelength controller to easily see if the SOA will be exceeded without having to do these calculations.

SINGLE TEC TEMPERATURE CONTROL

In most scenarios, a single TEC can be properly chosen that will fit the parameters of the application, and perform temperature control to within the stability required. Application Note [AN-TC09] provides more information regarding single TEC use.

When using a single TEC, wiring and sensing the temperature is simple. **Figure 2** provides an example setup.

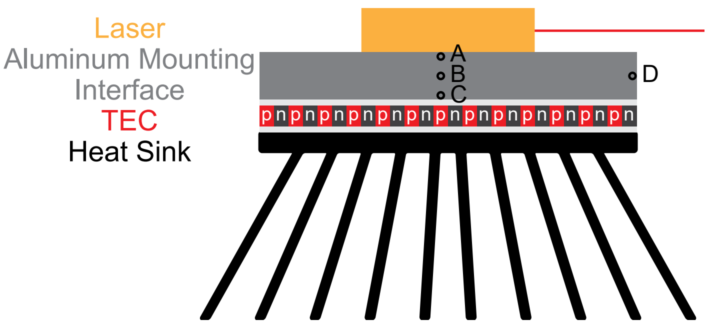

Figure 2. This example shows three good (A-C) locations and one poor (D) location for possible sensor placement. Point A would give the maximum accuracy for temperature measurements.

The setup in **Figure 2** consists of a single TEC, an aluminum block for mounting, a heatsink, and a laser that needs to be temperature stabilized.

Points A, B, and C show three different options for placing a temperature sensor. If maximum accuracy is required, embedding the sensor at point A would be the proper choice due to its proximity to the laser. This choice will also allow better tuning of PID parameters on the controller. If less accuracy is acceptable, point B or C would be a good choice. Point C typically provides better stability than A or B due to its proximity to the TEC. Note that all three choices are in the center of the apparatus, not the edges. The sensor should be embedded in the block, not placed on an outside edge (D).

The wiring of a single TEC is straightforward. Simply attach the positive/negative leads of the TEC to the positive/negative terminals of the TEC controller.

AVOIDING COMPLIANCE-LIMITED OPERATION WITH A SINGLE TEC

The term "compliance voltage," which is the maximum voltage available to the TEC, is defined as the total supply voltage minus the voltage required to operate the TEC controller. Mathematically, this is expressed as

$$V_C = V_{PS,MAX} - V_{CONTROLLER}\ , \qquad \textbf{(6)}$$

where V_C is the compliance voltage, $V_{PS,MAX}$ is the maximum power supply voltage, and $V_{CONTROLLER}$ is the voltage drop across the temperature controller.

In practice, the TEC cannot require more voltage than the control electronics can provide. Thus, for a single TEC, ensure the controller meets the current/voltage requirements of the TEC and the application.

Example 1: Single TEC Compliance Voltage Calculation

Consider a controller with a maximum current of I_{MAX} = *15A*, and V_C = *20V*. What TEC resistance will cause the system to become compliance-limited when operating at maximum current?

Using Equation (2) with the parameters given,

$$20V = (15A)(R_{TEC})\ , \qquad \textbf{(7)}$$

solving for R_{TEC},

$$R_{TEC} = 1.33\Omega\ . \qquad \textbf{(8)}$$

Any TEC resistance above 1.33Ω will cause the system to be compliance-limited.

Example 2: Impact of a Poorly Chosen TEC

Consider the same parameters as above (controller specifications of I_{MAX} = *15A*, and V_C = *20V*). What impact would choosing a TEC with resistance of 1.5Ω have on the system if 15A of current is required for the application?

Recall from Example 1 that any resistance above 1.33Ω will cause the system to be compliance-limited. Again, using Ohm's Law,

$$20V = (I_{OP,\ MAX})(1.5\Omega)\ , \qquad \textbf{(9)}$$

where $I_{OP,\ MAX}$ is the maximum operating current, in Amps. The compliance voltage of 20V was substituted for *V*, since the system is compliance-limited. Solving for $I_{OP,\ MAX}$,

$$I_{OP,\ MAX} = 13.33A\ , \qquad \textbf{(10)}$$

which is less than the desired operating current of 15A. This shows that if the system is compliance voltage limited, the maximum current delivered will be less than expected.

MULTIPLE TEC TEMPERATURE CONTROL

If the application requires multiple TECs for temperature control, the scenario becomes more complicated. The TEC location, wiring, and sensor placement are all parameters that need to be considered.

CCD arrays, multiple lasers, and large masses (metal blocks being used for mounting optics, optical tables, etc.) are all instances that might require multiple TECs for adequate thermal stability.

PROPERLY ARRANGING MULTIPLE TECS

The placement of the TECs is important when dealing with more than one. The goal is to maximize the amount of surface area of the mounting interface that is in contact with the TEC. Ideally, 100% of the material needing to be thermally controlled would be in either direct, or secondary contact with the TEC. For example, in **Figure 2**, the TEC fully covers the base of the aluminum mounting block, which is in thermal contact with the device needing to be controlled. It is important that the aluminum block, or its equivalent in a different scenario, is a good thermal conductor, and it is advised that thermal paste is used on all thermal interfaces.

Wavelength recommends connecting the TECs thermally in parallel (all mounted onto the same plane, not placed vertically on top of each other[1]). The left side of **Figure 3** shows two examples of TECs that are mounted thermally in parallel.

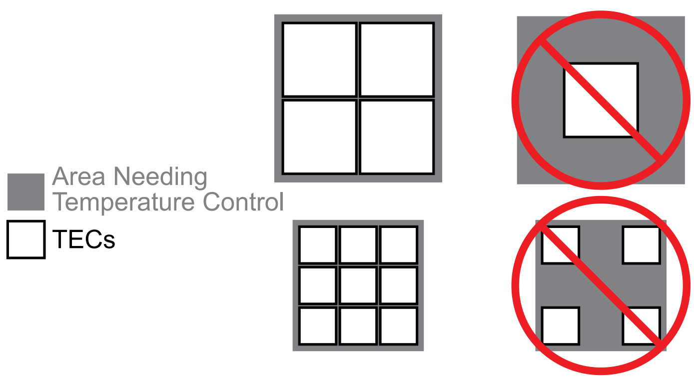

Figure 3. Proper placement of TECs shown on the left. Note the minimal uncovered surface area, and the close placement of the individual TECs to each other.

1 When TECs are stacked vertically, one on top of the other, it is called a "multi-stage" configuration. Multi-stage operation can lead to a larger temperature differential, but has less efficiency than the method described here.

WIRING MULTIPLE TECS

Since the temperature differential between TEC plates is determined mainly by the current flowing through the TEC, Wavelength recommends that TECs are electrically wired in series (see **Figure 4**). By wiring multiple TECs in series, it is guaranteed that each TEC is receiving the same amount of current.

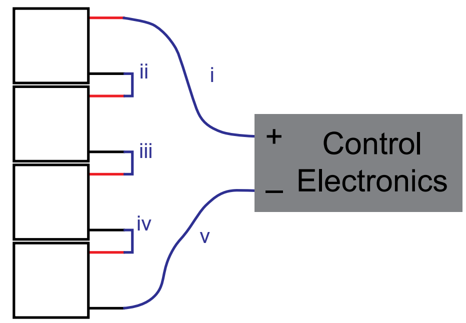

Figure 4. Make the blue connections (labeled i-v) to wire multiple TECs in series. Current will flow from the positive terminal of the control electronics, and through each TEC one after the other, before returning to the negative terminal of the control electronics.

If the TECs are wired in parallel, the amount of current to each is determined by its individual impedance. If these impedances are not identical, the current to each TEC will be different. This will lead to unequal temperature differentials across each TEC. This can result in major oscillations in temperature. When wired in series, the voltage drop across each TEC is different, but the current is the same. When wired in parallel, the current through each TEC is different, while the voltage across each is the same.

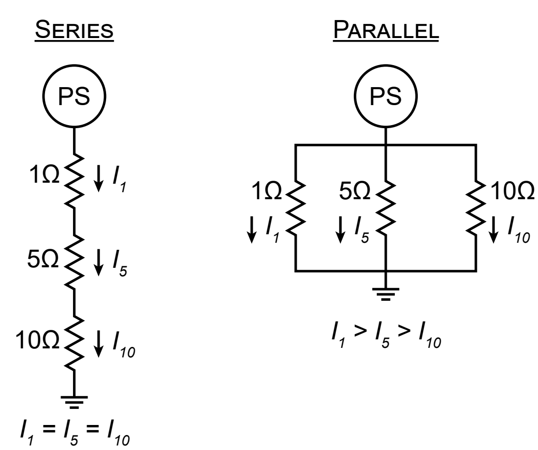

Figure 5. The rules governing the current through three resistors changes, depending on whether the configuration is wired in series or in parallel.

The left-hand side of **Figure 5** shows three resistors in series, with resistances of 1Ω, 5Ω, and 10Ω respectively. The equivalent resistance is then

$$R_{EQ,\ SERIES} = 1\Omega + 5\Omega + 10\Omega\ , \qquad \textbf{(11)}$$
$$R_{EQ,\ SERIES} = 16\Omega\ .$$

Since there is only one path for the current to follow, the total resistance determines the current through the system. All of the resistors receive the same amount of current. Solving for the current in this scenario,

$$I_{SERIES} = V_{PS} / R_{EQ,\ SERIES}\ , \qquad \textbf{(12)}$$
$$I_{SERIES} = V_{PS} / 16\Omega\ .$$

Since each resistor gets the same amount of current, the ranking is

$$I_1 = I_5 = I_{10}\ , \qquad \textbf{(13)}$$

where I_1 corresponds to the current through the 1Ω resistor, I_5 is the current through the 5Ω resistor, and I_{10} is the current through the 10Ω resistor.

In comparison, the right-hand side of **Figure 5** shows the same three resistors wired in parallel. In this case, there are multiple paths for the current to follow. The current will want to follow the path of least resistance, meaning that the resistor with the lowest value will receive the most current. Mathematically, this is expressed as

$$I_R = V_{PS} / R\ , \qquad \textbf{(14)}$$

where I_R is the current through a given resistor, and R is the resistance of that resistor.

In this case, the equivalent resistance does not need to be found in order to calculate the current through it. This is because the current splits based on the individual resistances. The current through each resistor is determined by its resistance and the power supply voltage. Thus, the currents in this case are determined by

$$I_1 = V_{PS} / 1\Omega\ ,$$
$$I_5 = V_{PS} / 5\Omega\ , \qquad \textbf{(15)}$$
$$I_{10} = V_{PS} / 10\Omega\ ,$$

making the ranking

$$I_1 > I_5 > I_{10}\ . \qquad \textbf{(16)}$$

SENSOR & DEVICE LOCATION WITH MULTIPLE TECS

Sensor placement and device location, while more complex than the single TEC case, follows the same rule previously stated. The sensor should be located in the middle of the thermal load, and the device to be controlled should be located in the center of the arrangement of TECs. **Figure 6** shows three examples of where to properly locate a sensor and device when dealing with a multi-TEC arrangement. The closer the sensor can be to the device under thermal management, the more accurate the reading is going to be.

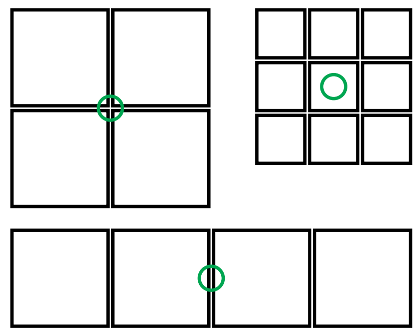

Figure 6. Place the temperature sensor and the device being thermally managed in the place indicated by the green circle for proper measurements when using multiple TECs.

AVOIDING COMPLIANCE-LIMITED OPERATION WITH MULTIPLE TECS

Along with the thermal considerations discussed in the previous section, staying below the compliance voltage is a crucial electrical issue when using multiple TECs.

Although the fundamental functionality of the TECs is determined by the current passing through them, there is also an associated voltage drop across each one. If the sum of the voltage drops across the TECs reaches the compliance voltage level of the controller, the controller cannot deliver maximum current. The TECs are now driven with a smaller current. The degree of freedom (voltage) that was available now is maxed out. Thus, the current output is a function of the compliance voltage, not the feedback to the controller.

Example 3: Compliance-Limited Operation With 4 TECs

Consider a case where four TECs are required (each with a resistance of 2Ω). The controller again has a maximum current output of 15A, and a compliance voltage of 20V. Operation at 5A is needed for proper temperature control. The TECs are wired in series, as recommended.

First, determine if the system will be compliance-limited. Using Ohm's Law,

$$V_{TECs} = (5A)(8\Omega) = 40V \,. \tag{17}$$

the total voltage drop across the four TECs at 5A will be 40V. This is double the compliance voltage of the controller, meaning the system is compliance-limited.

Since the system is compliance-limited, the maximum current available to the TECs is

$$\begin{gathered} I_{OP} = V_C \,/\, R_{TOT} \,, \\ I_{OP} = 20V \,/\, 8\Omega \,, \\ I_{OP} = 2.5A \,. \end{gathered} \tag{18}$$

Thus, due to the compliance-limited operation, only half of the required current is available to the TECs.

At voltages less than the compliance voltage, there is some overhead in the amount of current supplied to the TECs. The controller can change the current through the TECs according to the sensor feedback. But, once the compliance voltage has been reached, that overhead vanishes, and sensor variation (temperature changes) will be ignored.

Example 4: Safely Planning the Number of TECs

In order to avoid the compliance voltage limit, both the number of TECs, as well as their resistance needs to be considered.

If 2A output current is desired, and the TECs are each 2Ω, how many TECs can be used while still keeping 4V of overhead? Assume the same controller specifications as the previous examples. The TECs are wired in series, as recommended.

The 4V of overhead means that the maximum voltage now becomes

$$\begin{gathered} V_{OP} = V_C - 4 \,, \\ V_{OP} = 20 - 4 = 16V \,. \end{gathered} \tag{19}$$

Using 16V as the new operating voltage, the number of TECs, *n*, can be found. With the TECs in series, their resistance simply adds, so

$$\begin{gathered} V_{MAX} = I_{OP} R_{TEC} \,, \\ 16V = (2A)(2\Omega)n \,, \\ n = 4 \,. \end{gathered} \tag{20}$$

Thus, the maximum number of 2Ω TECs that can be operated at 2A while maintaining a 4V overhead is 4. The amount of overhead in current (I_{OH}) is given by

$$\begin{gathered} 4V = I_{OH}\,(8\Omega) \,, \\ I_{OH} = 0.5A \,. \end{gathered} \tag{21}$$

Example 5: Finding Overhead in Current

As a final example, calculating the voltage required for a given amount of desired overhead in current will be shown.

If normal operation of 1A is required with 2A of overhead desired, and the setup includes two 2Ω TECs, how much compliance voltage is required? The TECs are wired in series, as recommended.

First, calculate the operating voltage,

$$V_{OP} = I_{OP} R_{TEC} \,, \qquad V_{OP} = (1A)(4\Omega) = 4V \,. \tag{22}$$

Under normal operation, 4V will be required. In order to have 2A of overhead, the maximum current will be 3A, making the maximum voltage V_{MAX}

$$V_{MAX} = I_{MAX} R_{TEC} \,, \qquad V_{MAX} = (3A)(4\Omega) = 12V \,. \tag{23}$$

Thus, in order to maintain 2A of overhead current from the normal operating level, an additional 8V is required from the power supply, making the compliance voltage requirement 12V.

In order to find the total voltage required for this scenario, the voltage required to operate the control electronics must be added to the compliance voltage.

If the control electronics require 2V to operate, then the total voltage required for this application is

$$V_{PS} = V_C + V_{CONTROLLER,\,1} \,, \qquad V_{PS} = 12V + 2V = 14V \,. \tag{24}$$

So, 14V is required of the power supply to power the control electronics, and provide 2A of current overhead for two 2Ω TECs wired in series.

All of this must be taken into consideration for designing a thermal management system with multiple TECs. The max current and voltage of the TECs and the TEC controller, along with the total resistance of (or voltage drop across) the TECs needs to be carefully planned out such that compliance-limited operation will not occur.

SCENARIOS TO AVOID

WIRING MULTIPLE TECS IN PARALLEL

Wiring the TECs in series is a deliberate choice to ensure that the current (the fundamental operation parameter) is the same through each of the TECs.

If the TECs were wired in parallel (as in **Figure 7**), the current going through each individual TEC would be proportional to the impedance of each TEC. Even the slightest difference in impedance would draw a different current.

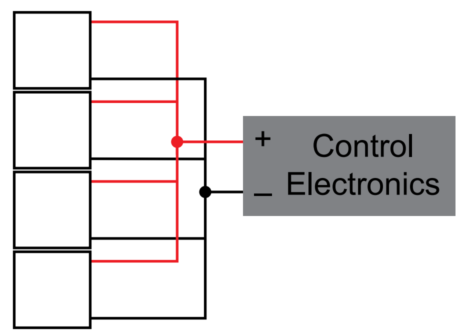

Figure 7. Wiring TECs in parallel (as shown) can lead to stability problems, due to impedance mismatch.

Since the temperature differential between the plates is first and foremost related to the current flowing through the TEC, if a constant temperature is desired, then the TECs should all be providing the same temperature. This is much more difficult if the TECs are not all receiving the same current from the controller.

USING MULTIPLE SENSORS WITH MULTIPLE TECS

When using a single TEC, there must be a sensor to provide feedback to the controller. However, if multiple TECs are being used, having a sensor for each one can lead to feedback and stability problems if a single controller is used.

For example, if four TECs are used, and each have their own sensor, which reading is the "actual" temperature? Consider a scenario similar to the bottom case of **Figure 6** (four individual TECs side by side, forming a row). If each of these TECs has an individual sensor, and each sensor is reading a slightly different temperature, then the controller has multiple, conflicting feedback mechanisms.

This is why Wavelength recommends using one sensor located in the middle of the thermal mass, as close as possible to the device being thermally controlled. This gives the most accurate temperature reading for feedback.

SUMMARY

Thermoelectric coolers are ideal for precisely controlling the temperature of small objects, due to their size and ease of use. Utilizing properly designed controllers, loads, and sensors enables stabilities as low as 0.0009°C.

Sometimes, a single TEC can be designed in such that the temperature differential required is achieved with the current and voltage constraints that are available. However, if multiple TECs are required, they should be wired in series, and care should be taken to avoid becoming compliance voltage-limited.

TECs should be mounted thermally in parallel, covering as much of the surface area as possible, and in good thermal contact with the unit under thermal management.

A single sensor, located centrally, should be used to provide feedback to the TEC controller. Multiple sensors introduce conflicting feedback, and can cause temperature oscillations, rather than stability.

Without careful planning, the compliance voltage limit can be reached much more easily with multiple TECs. If this happens, the controller no longer has the ability to make changes to the temperature based on the active feedback.

If all of the above parameters are taken into account, it is possible to use multiple TECs to very precisely control the temperature of a given object.

USEFUL LINKS

1. AN-TC09: Specifying Thermoelectric Coolers
2. AN-TC10: Temperature Controller Basics
3. SOA Calculator for Temperature Controllers

KEYWORDS

compliance voltage, Ohm's Law, thermoelectric cooler, TEC, temperature controller, Peltier effect, PID control, feedback, active feedback, thermistor, thermal stability, series, parallel, Safe Operating Area, SOA

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A	August 2017	Initial Release