

Temperature Measurement with Thermocouples

Application Note

Introduction

Temperature measurement generally can be divided into two main categories – contact thermometry and radiation thermometry.

Contact thermometry consists of a thermocouple which always remains in contact with the device under test, while radiation thermometry measures the radiation of the device under test without contact, by means of an infrared sensor.

In order to guarantee a long lifetime for LEDs, the junction temperature must not be exceeded. The maximum junction temperature is specified in the data sheet for the LED.

This application note provides information about measurement procedures, the thermocouples used and their systematic errors as well as the ways in which thermocouples are mounted.

Explanation of underlying circumstances

Since the LED junction temperature cannot be measured directly, it is necessary to take measurements at another defined point. An appropriate location is the solder point, since the thermal resistance R_{thJS} between the solder point and the junction is fixed by the package design and can be obtained from the corresponding data sheet. For a particular solder point temperature T_S , the junction temperature T_J can be calculated, allowing the junction temperature, drive current and thermal characteristics for varying ambient temperatures to be obtained.

The calculation of the LED junction temperature for a given solder point

temperature is described in the application note “Thermal Management of SMT LED“.

Functionality of a thermocouple

Thermocouples are the most commonly used temperature sensors; accurate temperature measurements can be made with a typical low-level voltmeter. The equipment required is relatively inexpensive.

A thermocouple simply consists of two different metal wires (for example, copper and constantan) which are welded together at one end, and then separated from each other with insulated leads. With the influence of heat at the welded junction, a DC voltage (thermocouple voltage) is produced between the two metals which can be measured and used to provide information about the prevailing temperature. The voltage generated by the thermocouple is largely proportional to the difference between the temperature of the device under test and the reference temperature.

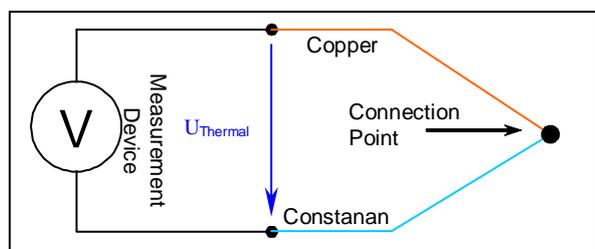


Figure1: Principle test arrangement for the temperature range of -200°C to $+600^{\circ}\text{C}$

Thermocouple selection

Various thermocouples are available which are differentiated according to type and construction:

Types of thermocouples, materials and color codes

Thermal Pair – Types, Materials, Color Codes			
Element Type	Standard	Material Combination	Color Code
Type T	EN 60 584	Cu - CuNi	
Type E	EN 60 584	NiCr - CuNi	
Type J	EN 60 584	Fe - CuNi	
Type K	EN 60 584	NiCr - Ni	
Type S	EN 60 584	Pt10%Rh - Pt	
Type R	EN 60 584	Pt13%Rh - Pt	
Type B	EN 60 584	Pt30%Rh - Pt	

Table 1 Color coding according to IEC 304

The insulation for the **negative lead** is white for all thermocouples.

The insulation for the **positive lead** has a color according to the above table.

Note:

Certain manufacturers use a different color coding or adhere to country-specific standards

According to IEC 60584, thermocouple types are subdivided into three tolerance classes:

Class	1
Tolerance (±) Type T	0.5°C or 0.004* t -40°C ... +350°C
Tolerance (±) Type E Type J Type K	1.5°C or 0.004* t -40°C ... +800°C -40°C ... +750°C -40°C ... +1000°C
Tolerance (±) Type R and S Type B	1°C or 1+(t-300)*0.003°C 0°C ... +1600°C
Class	2
Tolerance (±) Type T	1.0°C or 0.0075* t -40°C ... +350°C
Tolerance (±) Type E Type J Type K	2.5°C or 0.0075* t -40°C ... +900°C -40°C ... +750°C -40°C ... +1200°C
Tolerance (±) Type R and S Type B	1.5°C or 0.0025* t 0°C ... +1600°C +600°C ... +1700°C
Class	3
Tolerance (±) Type T	1.0°C or 0.015* t -200°C ... +40°C
Tolerance (±) Type E Type J Type K	2.5°C or 0.015* t -200°C ... +40°C -200°C ... +40°C
Tolerance (±) Type R and S Type B	4°C or 0.005* t +600°C ... +1700°C

Table 2 Tolerance classes according to IEC 60584

		Spec. Resist. ρ $\frac{\Omega \cdot \text{mm}^2}{\text{m}}$
Copper Cu:	≈100% (pure copper)	0.017
Constantan CuNi:	55% Cu, 45% Ni or 55% Cu, 44% Ni, 1% Mn	0.495
Iron Fe:	≈100% (pure iron)	0.11
Nichrome NiCr:	90% Ni, 10% Cr	0.72
Nickel Ni:	95% Ni, rest Mn, Al, Si	0.27
Platinum Rhodium:	90% Pt, 10% Rh	0.193
Platinum:	≈100% (pure platinum)	0.107

Table 3 Material Composition

Since these measurement procedures involve contact thermometry, a systematic error is introduced. When attaching a thermocouple, energy is dissipated. Therefore, it is important to know which level of accuracy is required.

In order to measure the LED solder point temperature T_s , a thermocouple of type K is recommended, since the thermal conductivity for this type is lowest and therefore less energy is dissipated than with other types. To minimize the occurrence of systematic errors, the dimensions of the thermocouple should be as small as possible.

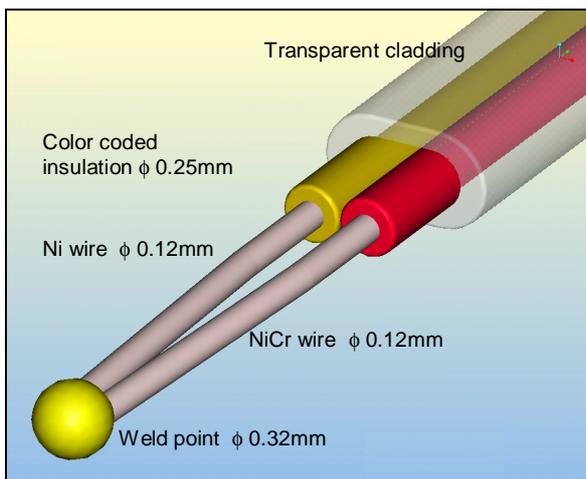


Figure 2: Thermocouple of type K

Mounting the thermocouple to the device under test

Several mounting methods are possible; however, only two methods will be presented:

1. Solder Method

Soldering guarantees that the thermocouple maintains good thermal contact with the device under test, and permits exact temperature measurement. In addition, the mounting point can be exactly determined. This good thermal coupling allows quickly varying temperatures to be accurately measured. However, this method has essentially three significant disadvantages:

An electrical connection is present between the thermocouple and device under test (no voltage isolation).

Thermal noise can arise during soldering which can create noticeable fluctuations in the thermocouple voltage.

In addition, EMI disturbances can arise, which influence the measurement sequence (for example, a cell phone at the measurement site).

2. Adhesive Method

Using an adhesive is an alternative to soldering. The primary advantage of an adhesive is the voltage isolation between the thermocouple and the device under test. Furthermore, the thermal resistance between the measurement object and the sensor is increased. This means, however, that less energy is dissipated from the thermocouple which inevitably causes the measurement to become sluggish and less precise.

Consideration should be given regarding the adhesive type and the secondary influences which arise at the mounting location.

A thermal adhesive such as Arctic Silver Adhesive, Arctic Alumina Adhesive or similar two-component thermal adhesive is recommended. These thermal adhesives are electrically nonconductive and have a thermal conductivity in the range of 7.5 W/mK. The adhesive is easy to administer and handle. Mix components A and B in a ratio of 1:1 on a glass surface. Apply the adhesive to the measurement site, and attach the thermocouple to the prepared location and then secure the component firmly in place. This can be accomplished with a rubber band or hot glue.

Make sure that there is not too much pressure on the thermocouple and that no undesired metal contact is present between the thermocouple and the LED. To be sure, the circuitry should be checked with an ohmmeter. In case of electrical contact, the procedure must be redone. After about 40 minutes, the adhesive is suitable for measurement purposes. A soldering iron can be used to remove the thermocouple, since most adhesives become fluid at this temperature.

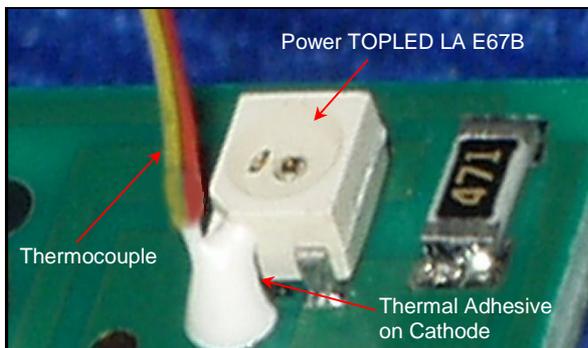


Figure 3: Thermocouple attached to a Power TOPLED®

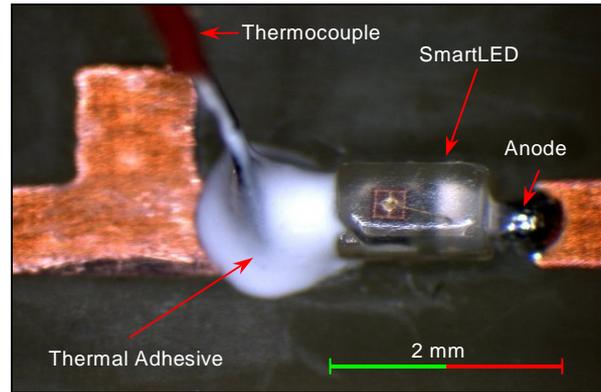


Figure 4: Thermocouple attached to a SmartLED®

Error estimation

The following error estimation is expressly for thermocouples of type “K” from OMEGA with the specific construction shown in Figure 2.

The error estimation is based on a series of experimental comparison measurements. *Comparison measurements carried out with an infrared camera and thermocouple showed no significant error for the thermocouples used.*

The following comparison measurements clarify that the error term arising from the energy transfer of the thermocouple is less than the tolerance bandwidth of the infrared camera ($\pm 2^\circ\text{C}$) and the thermocouple ($\pm 2.2^\circ\text{C}$).

The specially built measurement device pictured in Figure 5 serves only for comparison measurements, permitting simultaneous measurements by infrared camera and thermocouple.

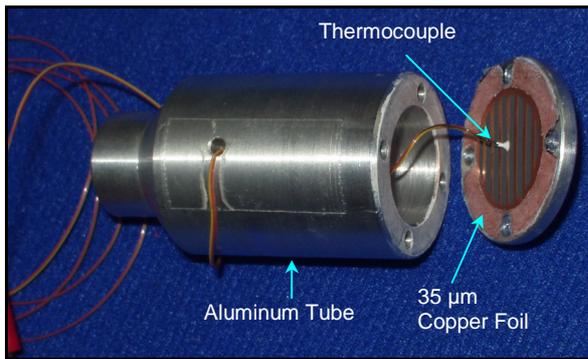


Figure 5: Measurement device

The measurement device is heated at the narrow end. The thick-walled aluminum cylinder serves to homogeneously distribute the heat to the contact surface. A specially etched copper foil (thickness 35µm) with thermally conductive paste, a fastening ring and four screws are mounted on the contact surface. A black foil with $\epsilon = 0.94$ is used as the emission converter for the camera. The thickness of the copper foil corresponds to the thickness of a solder pad which is normally used with LEDs. This permits the effect of the thermocouple to be visualized with the aid of an infrared camera.

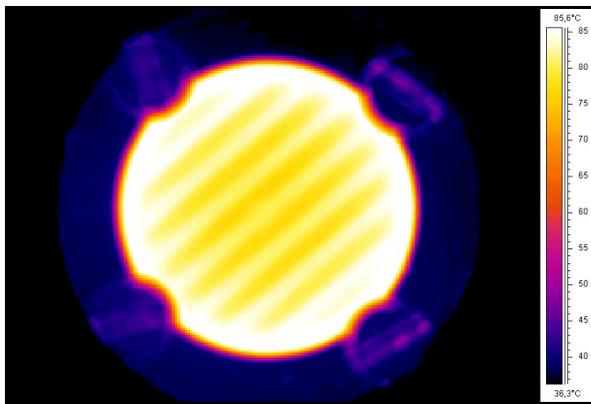


Figure 6: Uncalibrated IR camera image

In the above IR image, the stripes of the 35µm thick and 1mm wide copper foil can be recognized (Figure 6). The brighter area (white) shows the temperature distribution of the copper foil the noticeable dark part (yellow stripes) indicate the symmetrical etched area on the foil. The yellow stripes

results from missing any thermal conductive material. No objective conclusion can be reached from this image, however; it only serves to provide a better idea.

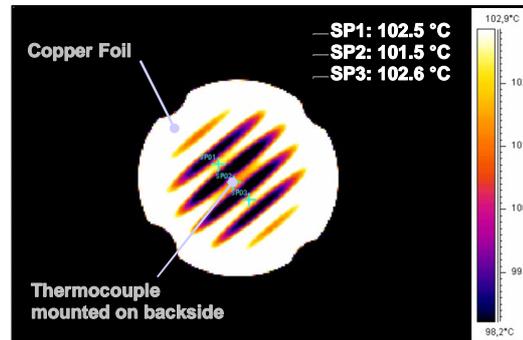


Figure 7: Calibrated IR camera image

In contrast, in this image (Figure 7), it is clear that the temperature at the thermocouple is lower than that of the two neighboring symmetrical strips. Specifically, the temperature deviation (error) in this image amounts to 1.0°C for a device temperature of around 100°C and an ambient temperature of 27°C.

Note:

The error increases with increasing temperature and decreases with decreasing temperature. In the operating temperature range of an LED (-40°C...+100°C) the error remains nearly linear.

Conclusion:

Since the error originating from the thermocouple of 1°C lies within the tolerance range of the IR camera and the range specified for the thermocouple itself, no further correction is necessary for the thermocouple with the dimensions and data shown in Figure 2.

Verification 1: SmartLED®

Solder point temperature measurement for a SmartLED® with IR camera and thermocouple.

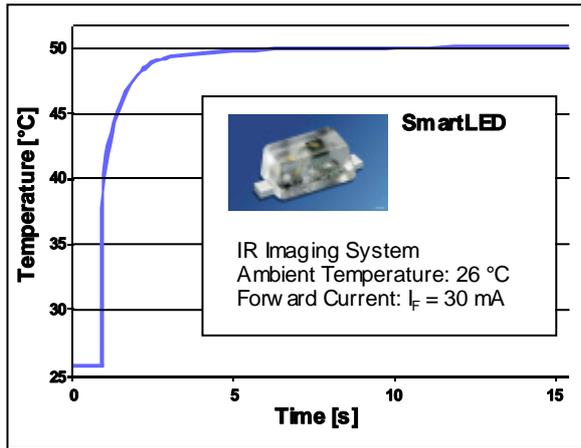


Figure 8a: Solder point temperature measurement of a SmartLED[®] with IR camera

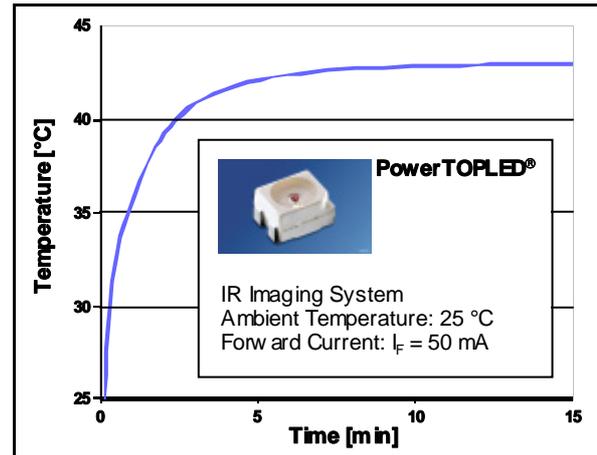


Figure 9a: Solder point temperature measurement of a PowerTOPLED[®] with IR camera

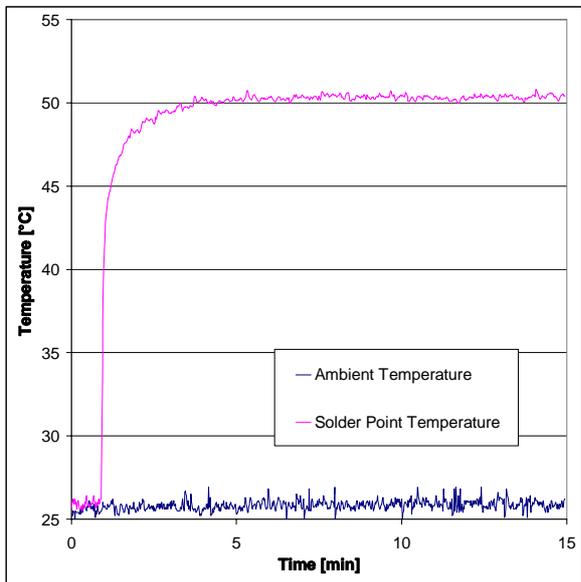


Figure 8b: Solder point temperature measurement of a SmartLED[®] with thermocouple

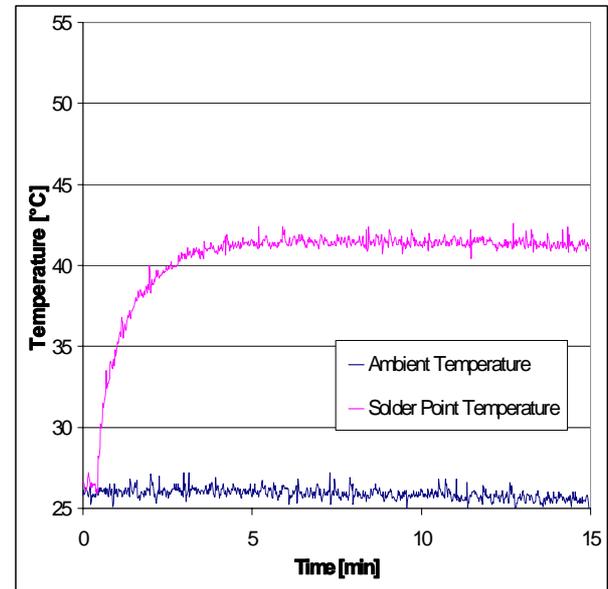


Figure 9b: Solder point temperature measurement of a PowerTOPLED[®] with thermocouple

Verification 2: PowerTOPLED[®]
Solder point temperature measurement of a PowerTOPLED[®] with IR camera and thermocouple.

Both verifications show very little deviation of the solder point temperature when measured with the thermocouple and infrared camera. This evidence confirms the above comparison for two different LEDs. No correction factor needs to be calculated, however, since the error for the two comparison measurements clearly lies within the deviation range of the instruments.

Important Information

1. Adhesives

In principle, one must ensure that the adhesive possesses a high thermal conductivity. Most thermal adhesives have a thermal conductivity of $> 7.5 \text{ W/mK}$, which is quite sufficient for this purpose.

Caution is advised when using cyanoacrylate-based adhesives (super glue): the thermal transmission is not particularly good and the adhesive is relatively brittle and unstable. Furthermore, an exothermic reaction occurs during hardening which causes a noticeable increase in temperature during the first ten minutes.

Polymer adhesives offer an alternative method of bonding. However, they are not all-purpose adhesives, and a UV lamp is additionally required. Furthermore, removal of the thermocouple is extremely difficult. Epoxy adhesives have a relatively long hardening time (ca. 5h), which requires that the thermocouple be fixed securely in place, and are therefore less appropriate in practice. Removal of the thermocouple is

relatively difficult, since this adhesive has a high mechanical cohesiveness.

In general, the bonding surface should be as small as possible, exhibit no electrical contact, and allow for removal of the thermocouple.

2. Power supplies for the device under test and measurement equipment

A stable power supply must exclusively be used for the device under test (e.g.: circuit board with LEDs) which is electrically isolated from the supply voltage (e.g.: a conventional power supply with a transformer). It should be noted that many switching power supplies do not have an isolating transformer, which can lead to unwanted voltage swings during the measurement process (Diagram 1). These voltage swings can also be observed from an attached thermocouple which is electrically isolated from the device under test (Diagram 1 and 2).

Faulty electrical isolation of the power supply for the device under test can be amplified to become an error and lead to feedback in the measurement equipment.

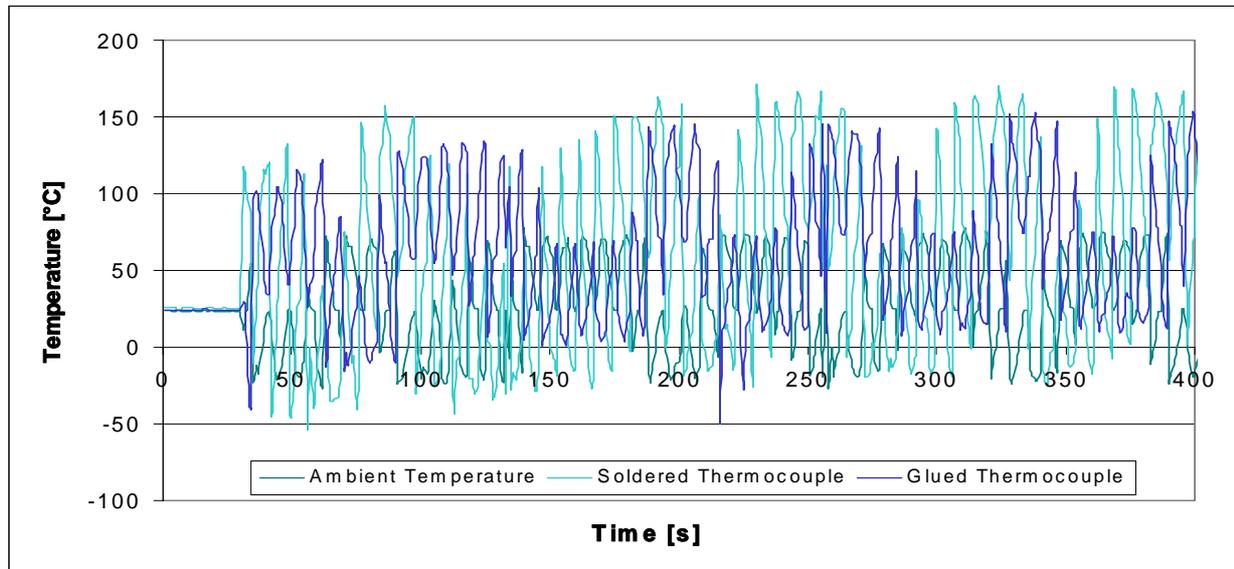


Diagram 1: Switching power supply without electrical isolation from power line

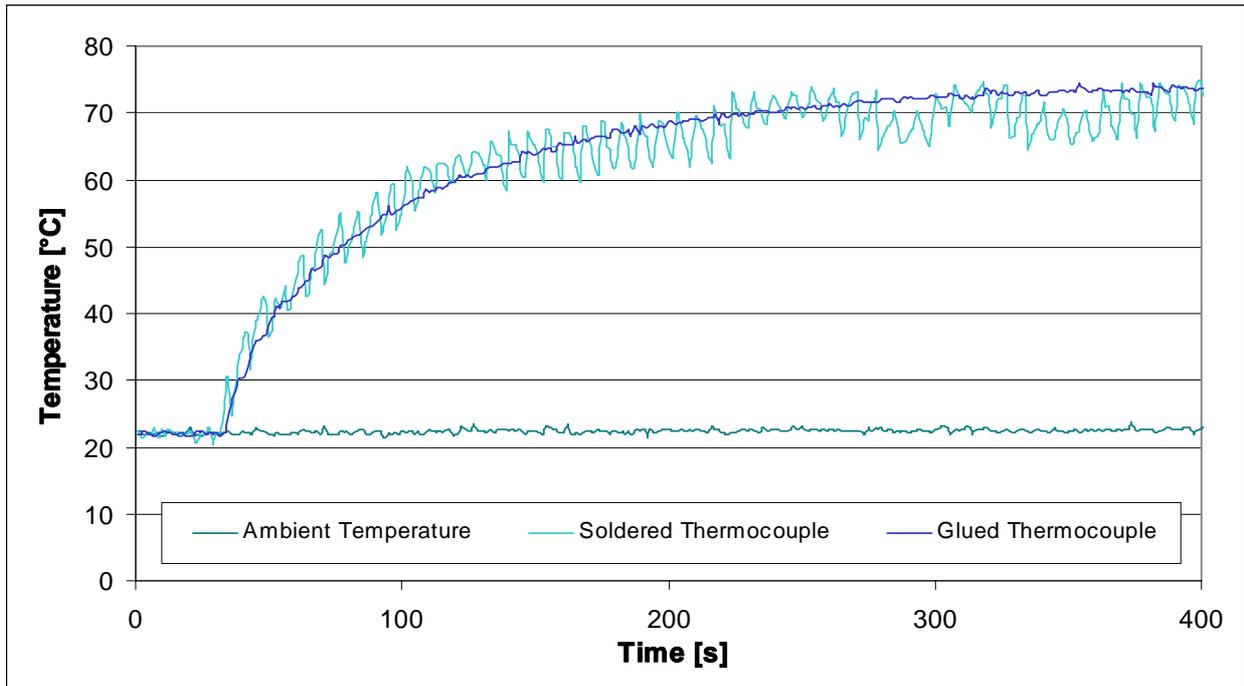


Diagram 2: Conventional power supply with electrical isolation from power line

In order to achieve a higher level of certainty and precision, it often makes sense to use a lead battery for the device under test.

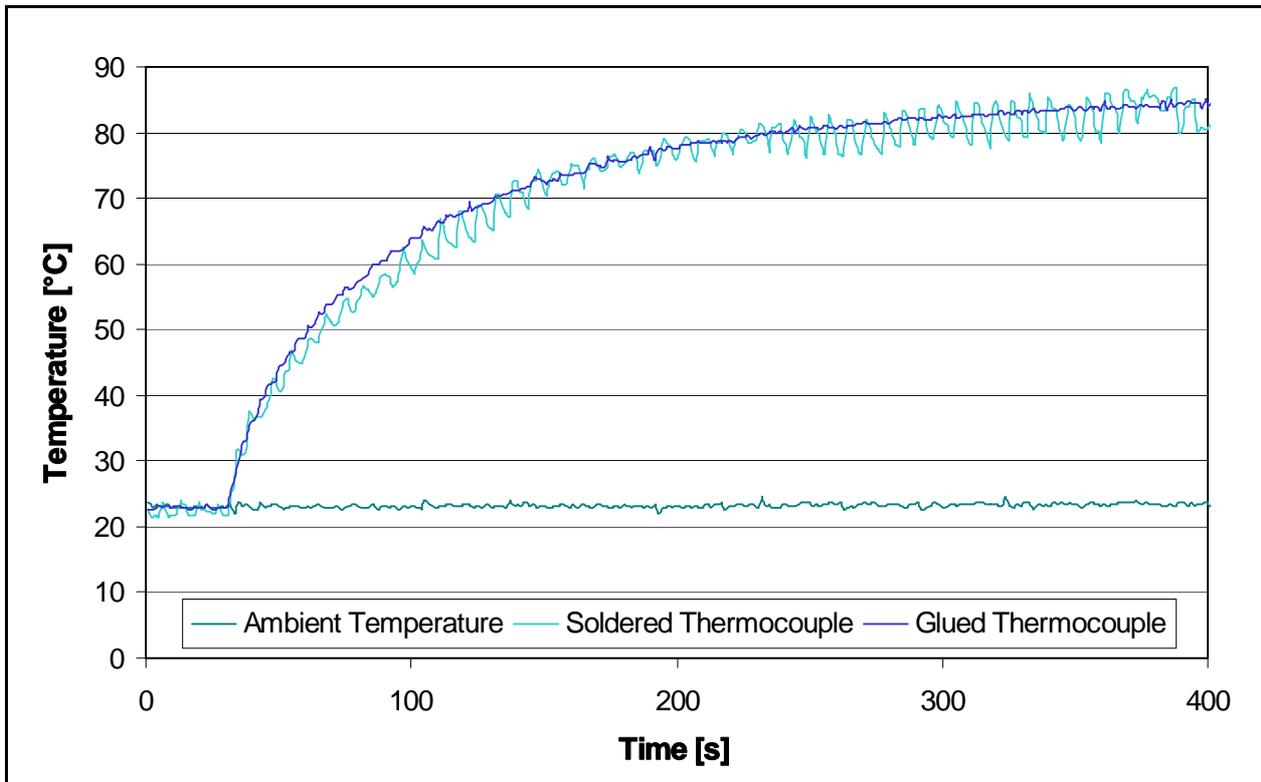


Diagram 3: Lead battery (lowest noise)

For thermocouples which are soldered in place, it is especially important to pay attention to which type of measurement instrument will be used and what type of power supply it has. Since the majority of thermocouples exhibit a thermocouple voltage of around 5mV at 100°C, the low voltage levels are susceptible to EMI. With battery powered measurement instruments (e.g.: VOLTKRAFT 502), electrical isolation of the device under test is less important, since no connection to the power line is present and therefore no feedback can arise.

Measuring Equipment

When selecting a measuring device, it is important to know whether only one discrete value or several discrete values will be measured over time.

For measuring a single value, a small handheld battery driven temperature measuring device with two connections for external thermocouples is recommended. The second connection is important for measuring the ambient temperature.

For recording several discrete values over time, a more elaborate instrument is required. At best, a multichannel instrument with computer interface (e.g.: Cambridge AccuSense TCM- 24) should be used, since the data is easier to manage, and is compatible with standard software (spreadsheet calculations).

This instrument is particularly precise, has a high sensitivity, an error correction unit, and offers the possibility to measure up to 24 thermocouples simultaneously. Because of the unit's high sensitivity and external power supply, the above indications should be observed.

Extending thermocouple leads

When thermocouple leads are extended, it has the effect of creating additional thermocouples at the connection points

which under certain circumstances can significantly influence the outcome of the measurement.

In case an extension is inevitable, the use of special clamps is highly recommended which serve to compensate for the errors which arise. In contrast to typically available serial connectors, thermocouple voltage connectors should be used, since their special construction expressly provides for pair wise connections. The contact bars consist of various metals and are individually matched to the material in the thermocouple. This permits the combination of metals in the temperature measuring element to be extended without interruption.

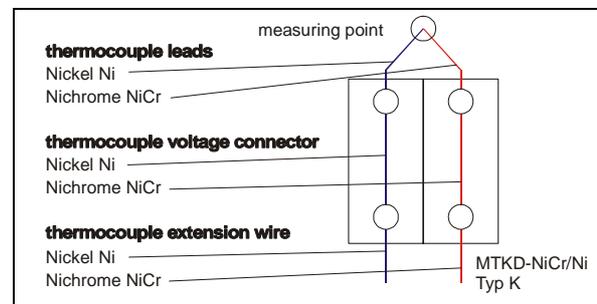


Figure 10a: Principle arrangement of thermal clamps

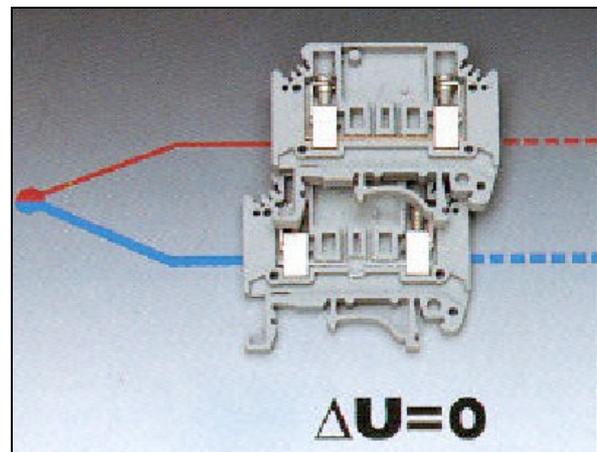


Figure 10b: Thermocouple voltage connectors connected with a thermocouple extension cable. Suitable for the temperature range of 0°C to +1200°C

Error Sources:

- **Thermocouple Polarity**

Reversing the polarity of the thermocouple results in incorrect measurement data.

- **Thermocouple Type**

The type of thermocouple used must also be set in the measurement instrument.

- **Extension of Thermocouple Leads**

Appropriate thermocouple voltage connectors must be used, corresponding to the type of thermocouple.

- **Mounting the Thermocouple**

Use an exact dosage of adhesive, limited to a small bonding area

- **Correct Location**

The correct measurement location is the solder point for the LED. However, it should be noted which terminal (anode or cathode) of the LED is thermally active. The correct terminal of the LED can be found in the OSRAM data sheet.

- **Correct Measurement**

Calibrate the measurement equipment;
Create the appropriate test environment;
Use or modify the original housing;
Avoid forced convection, if not desired;
Avoid direct sunlight;
No metal objects should be used as a platform, mounting assembly, etc;
No contact should occur outside of the weld point of the thermocouple;

- **EMI**

Cell phones, powerful transmitters and phase control devices can have a negative effect on the measurement sequence.

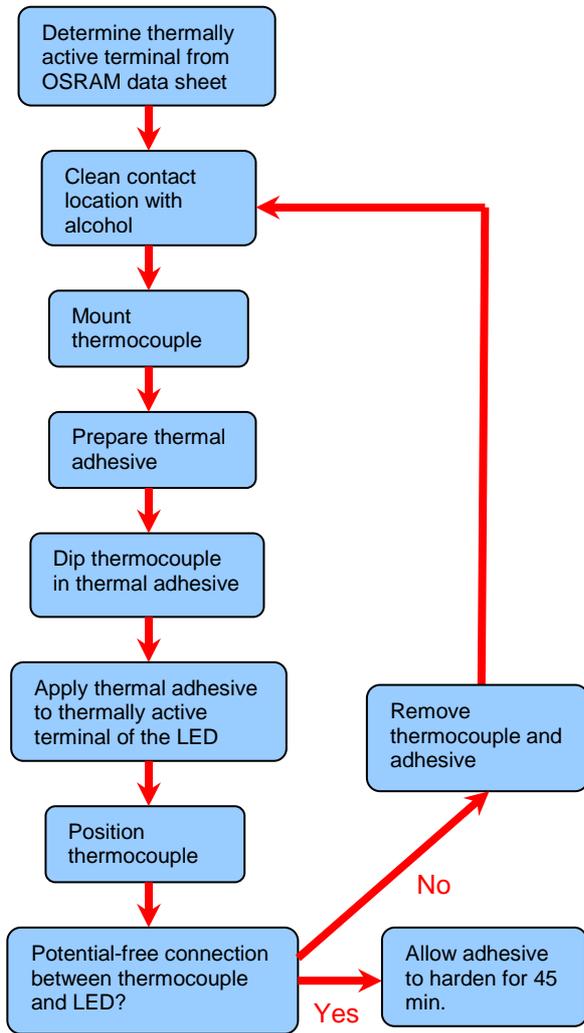
- **External Power Supply**

Devices with external power supplies, PC interfaces and the device under test should be electrically isolated from the power line. Warning: many switching power supplies have no electrical isolation.

- **Voltage Isolation**

Strong fluctuations of the measurement data can occur when the thermocouple is soldered in place. This effect rarely occurs for thermocouples which are mounted with adhesives. If this does occur, the mounting procedure should be repeated.

Brief Instructions: Mounting the thermocouple to the device under test



Summary

Temperature measurement by means of thermocouples is a multilaterally applicable method. In many cases, it is not possible to use infrared cameras, pyrometers and other temperature sensors for temperature measurement. Thermocouples prove to be well suited for these applications.

The advantages and disadvantages of this method are based on a series of numerous measurements. These measurements were repeated several times and verified with various LEDs. In addition, some measurements were performed with boundary values and constraints.

By comparison measurements and other measurement techniques, an error estimate can be made. The analysis of these measurement procedures shows that one can achieve satisfactory results regarding

the physical principles with relatively inexpensive equipment. Bonding the thermocouple with "Artic Silver Thermal Adhesive" has proven to be a reliable mounting method.

Sources:

Thermocouples & measuring equipment

www.omega.com

General sources for thermal management

www.electronics-cooling.com

www.coolingzone.com

Author: Rainer Huber

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