Application Note

Improving Thermal Response Time and Accuracy in High-Voltage Applications

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ABSTRACT

Effective temperature monitoring in high-voltage environments, such as automotive on-board chargers (OBC), DC/DC converters, and EV DC fast chargers, is crucial for maintaining safety and performance. These applications require isolated ICs because direct electrical connections can be hazardous and lead to inaccurate readings due to electrical noise and interference. Traditionally, negative temperature coefficient (NTC) thermistors sense temperature across isolation boundaries. This typically involves either using a high-voltage NTC with an isolated ADC or amplifier, which adds cost and complexity, or placing a standard NTC across the clearance gap from the high-voltage heat source, which results in poor temperature response time and significant measurement errors due to the thermal lag across the gap.

ISOTMP35 or ISOTMP35-Q1 solves these issues by providing a new isolated temperature sensor technology that allows to directly connect to a high-voltage heat source. This direct connection enables a much faster temperature response time of 3.1 seconds, compared to 78.3 seconds for NTC without epoxy and 47.8 seconds with epoxy. Additionally, ISOTMP35 achieves a more accurate final temperature of 72.1°C, making sure of better performance and reliability.

This application note demonstrates how ISOTMP35 enhances temperature response over other temperature sensing designs. By leveraging advanced isolation techniques and thermal management strategies, ISOTMP35 helps improve the safety and efficiency of critical applications such as automotive OBCs, DC/DC converters, and EV DC fast chargers, addressing the increasing power density and thermal challenges in modern EVs.

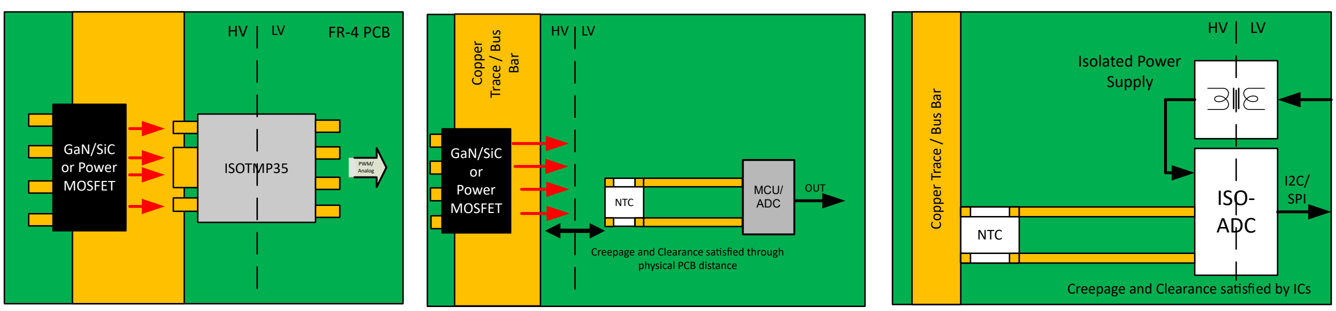

Figure 1-1. Examples of Different Temperature Sensing Designs

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1 Introduction

1.1 Calculating Thermal Response Time

Temperature response time is defined as the 63% rise time from an initial temperature to a final temperature.

There are multiple ways to specify temperature response time. For a traditional temperature sensor, there are usually two methods: with stirred liquid (oil), and in air (still or moving). Temperature response time in stirred oil is done by taking sensors that are in an oil bath at one temperature, typically 25°C, then moving them very quickly to another oil bath at a different temperature. Temperature response time in air, is usually tested by plunging sensors from an ambient air environment into an oven at a specific temperature. If the sensors are plunged directly into the oven, that is *moving air* since the oven is moving air around on the inside. To achieve *still air*, the user can plunge the sensors into an enclosed box inside the oven, so the air does not circulate and remains still.

However, for an isolated temperature sensor, directional response time is also used. Directional temperature response time tests how the sensor responds when one side is exposed to heat, while the other side is not. This replicates a real use case scenario, where the ISOTMP35 can be connected to a high voltage pad or bus bar, and that high voltage area is generating heat. This test provides a repeatable and simple method to evaluate how an NTC performs while electrically isolated in the low voltage region and how the ISOTMP35 performs while directly connected to a high voltage heat source.

Figure 1-1 is an example of measuring the 63% rise time.

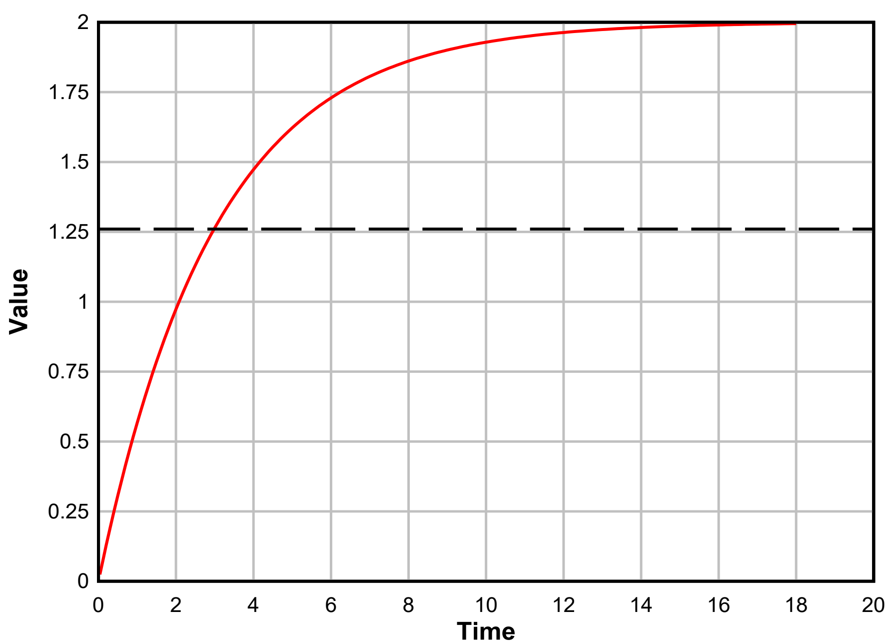

Figure 1-1. 63% Rise Example

This example is a generic decaying exponential rise, with a 63% rise time value of 1.26, final value of 2. This curve is given by Equation 1.

$$y = 2 \times \left(1 - e^{-\frac{t}{3}}\right) \tag{1}$$

The 63% time is 3s, and is determined by the denominator in the exponential. This is considered to be 1 tau on an exponential curve.

1.2 Current Design with Non-Isolated Temperature Sensors

Currently, sensing temperature across an isolation boundary can be done with a non-isolated temperature sensor, such as an NTC. Isolation devices that can normally bridge an isolation boundary in a high voltage environment must meet a minimum clearance threshold depending on the high voltage level. If using a non-isolated device, it must be placed a minimum distance from the isolation boundary specified by the clearance. Clearance is the shortest distance in air between the high voltage signal pin and a low voltage signal pin. Creepage is similar to clearance, it describes the shortest distance between the high voltage and low voltage sides of a device along surfaces, such as the package or the PCB. Creepage can never be less than clearance. The minimum clearance required is determined by multiple factors, although it is primarily determined by the working voltage of the isolated device.

In the case of ISOTMP35, which is a basic isolation device, the minimum clearance is 4mm (the width of the package body). If not using an isolated temp sensor, a user must place their non-isolated sensor across the high voltage boundary at least as far away as the minimum clearance. The main drawback with this method is that while it is easy to implement, placing the sensor in the low voltage region several millimeters away from the high voltage heat source means the heat must pass across FR4 (standard PCB dielectric) which has a relatively poor thermal conductivity. This means temperature response time is reduced and the final achieved temperature is much lower than what it can be with a direct connection.

Table 1-1. Thermal Conductivity (W/mK) of Common Media

Medium	Thermal Conductivity (W/mK)
Galden Oil	0.065
FR4	0.2
Gallium	29
Graphite	200
Copper	400
Graphene	1500

FR4 has relatively poor thermal conductivity, which means that the NTC can respond slowly to the change in temperature in the high voltage region and hence has both slow temperature response time and does not closely approach the final true temperature value. Both response time and final temperature value can be improved by using a non-conductive thermal epoxy to thermally couple the NTC with the high voltage heat source. While this can improve the thermal performance of the NTC, the performance is still not as good as direct metal-to-metal contact with the high voltage heat source.

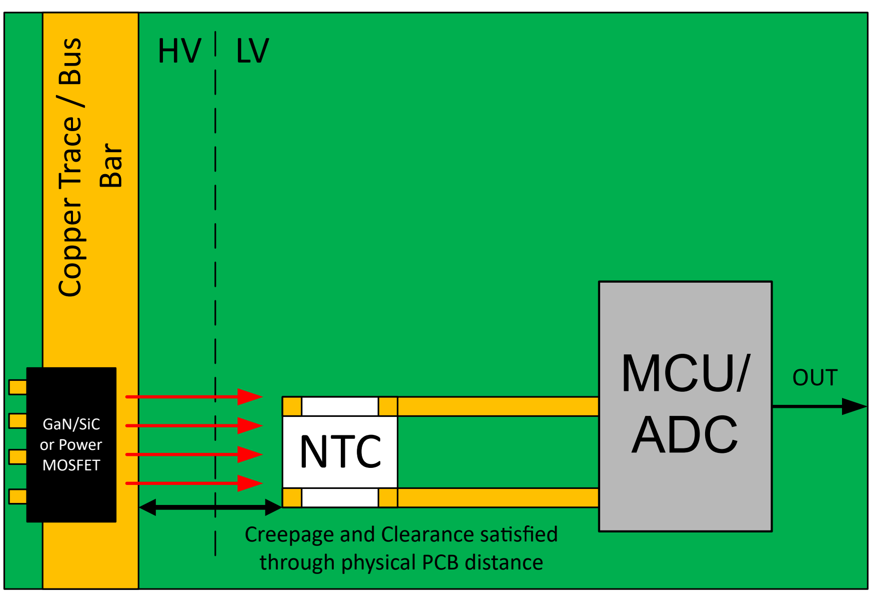

Figure 1-2. Low Voltage NTC Design

1.3 Proposed Design Using the ISOTMP35 Isolated Temperature Sensor

ISOTMP35 is an analog temperature sensor that is capable of being placed across a high voltage isolation boundary. This allows the ISOTMP35 to be placed directly onto either a high voltage bus bar or onto the heat sink of a high-power FET. Because of this direct contact, heat does not need to transfer through PCB material to make it across the isolation boundary, but instead the direct contact provides immediate temperature response and a much more accurate final temperature value. This is important because a faster response time and more accurate final value can help provide better overheating protection in a variety of customer systems.

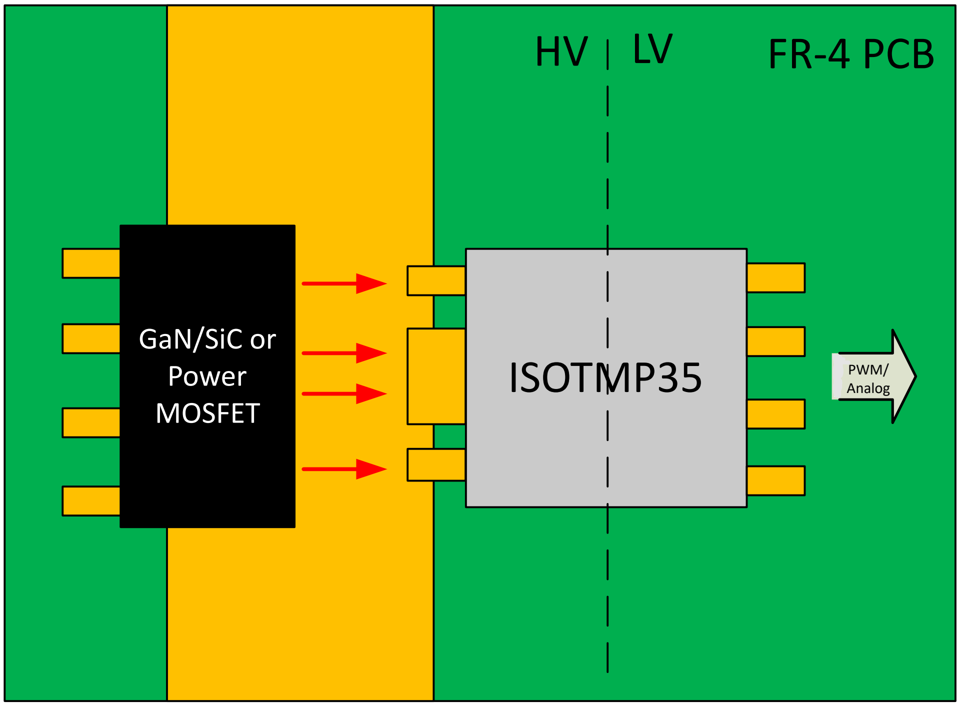

Figure 1-3. ISOTMP35 Example

2 Experiment Setup

To prove the theory that the ISOTMP35 would provide superior response time to an NTC design, an oil bath was used to compare the ISOTMP35 with an NTC. The experiment was then repeated with an NTC with thermal epoxy.

The experiment is done by pouring liquid gallium inside of a crucible, which is heated by an oil bath set to 75°C. Then a PCB with a 1 square inch copper pad (2oz copper) and the device under test is submerged in that liquid gallium to observe how the device's temperature changes over time.

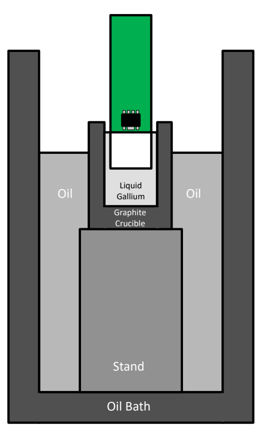

Figure 2-1. Response Time System Diagram

2.1 Step 1: Prepare the Oil Bath

The thermal response setup used a Fluke 7340 oil bath, heated to 75°C (ambient temp is 25°C) with the lid off. A metal stand is placed inside the oil, but does not exceed the height of the oil so it stays fully submerged.

A graphite crucible is placed on top of the metal stand, with a 3D-printed ABS insert designed to fit the test PCB. Then the crucible is filled with liquid gallium. The working principle is that the crucible can be surrounded by the hot oil, so it can heat the liquid gallium very quickly. The top of the crucible is exposed to the air, so that the test PCB can be inserted without contacting the oil.

Liquid gallium is used because it has a thermal conductivity of 29W/mK and it can be liquid at room temperature. The oil bath uses Galden HT-200 oil, which has a thermal conductivity of 0.065W/mK, so it isn't viable on its own for this test. Furthermore, the oil moves around while the bath is running, so it is impossible to control the submersion depth. The gallium inside the crucible is then heated to 75°C, and verified with a thermometer.

2.2 Step 2: Prepare the Liquid Gallium

The boards being testing use no high voltage signals, but use a 1 square inch copper pad to mimic a high voltage heat source. The board is submerged in the liquid gallium, to fully submerge the copper pad only. The liquid gallium is poured into the crucible, coming up to the bottom of the ABS lid. The same amount of liquid gallium is poured each time, making sure that the test conditions are consistent between runs.

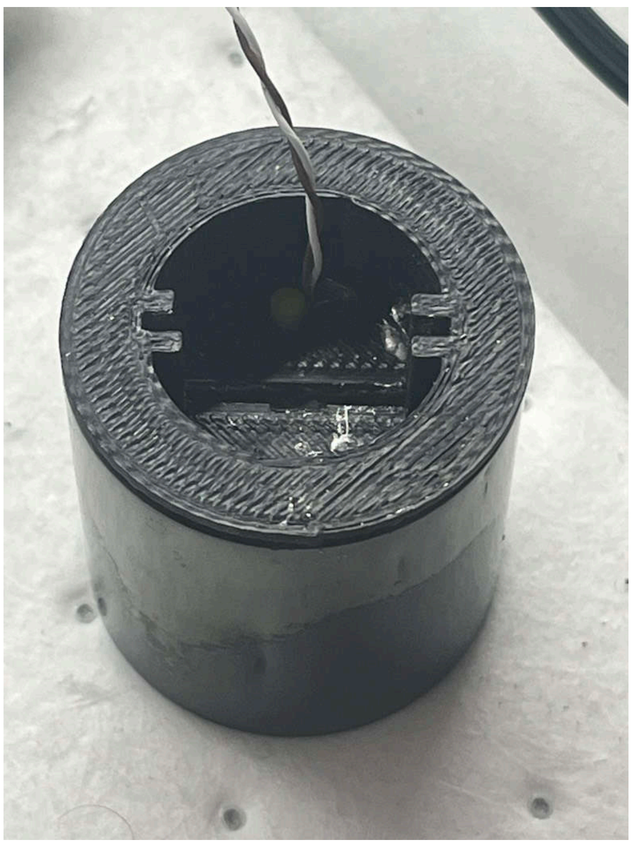

Figure 2-2. Empty Crucible

Figure 2-3. Crucible Filled with Liquid Gallium Placed in Oil Bath

2.3 Step 3: Submerge the Copper Pad

The liquid gallium rises exactly to the edge of the copper pad, marked by the white arrows. The copper pad extends under the solder mask, up to the edge of the package (marked by the line inside the white arrows). The ISOTMP35 is thermally connected to the copper pad via being soldered to it. However, no part of the ISOTMP35 package can actually make direct contact with the liquid gallium. This is done to make sure all the thermal energy the ISOTMP receives comes from the thermal conductivity of the copper, not the liquid gallium pouring right onto the sensor.

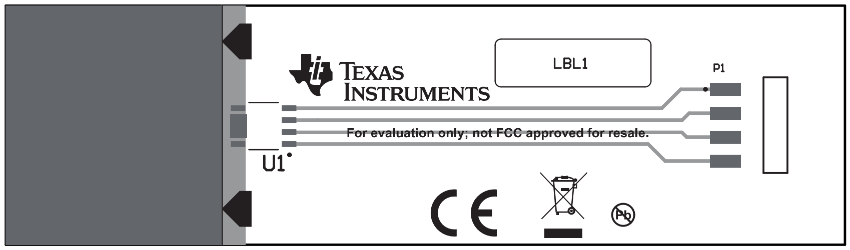

Figure 2-4. PCB Layer View of Test PCB

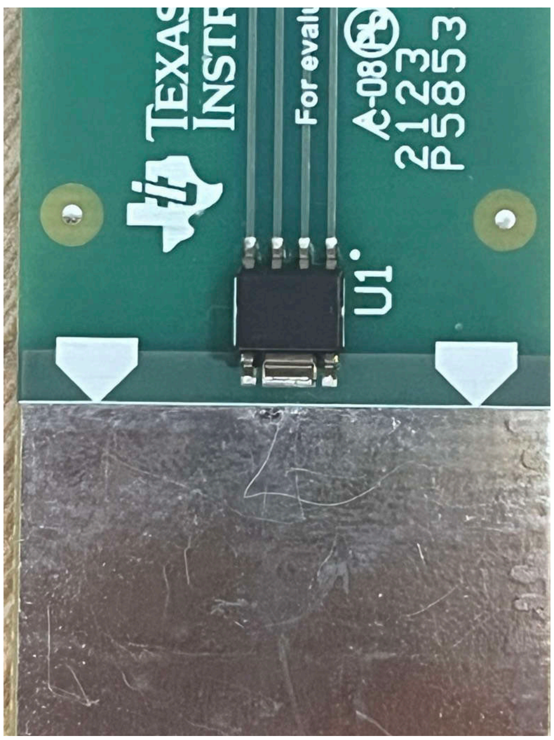

Figure 2-5. ISOTMP35 Mounted on Test PCB

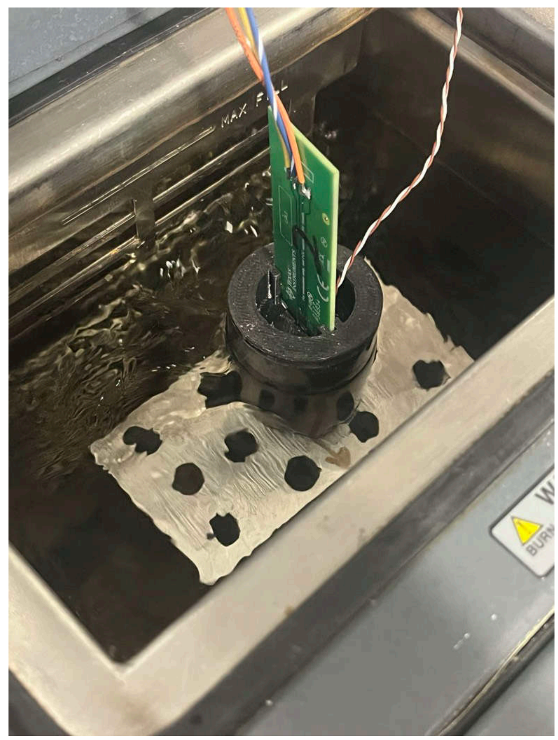

Figure 2-6. Test PCB Placed in Liquid Gallium for Thermal Response Test

2.4 Step 4: Prepare Each PCB Configuration

For the experiment, three options were tested: the ISOTMP35, an NTC soldered just across the clearance boundary, and an NTC thermally coupled to the copper pad with thermal epoxy, 2 boards each.

The thermal epoxy chosen was Dycotec Materials Ltd DM-TIM-15340-SYP, which is a thermal epoxy with a thermal conductivity of 3.7W/mK. While this is less than the 400W/mK conductivity of a direct copper connection, it is still a significant improvement over the 0.2W/mK conductivity of FR4 alone.

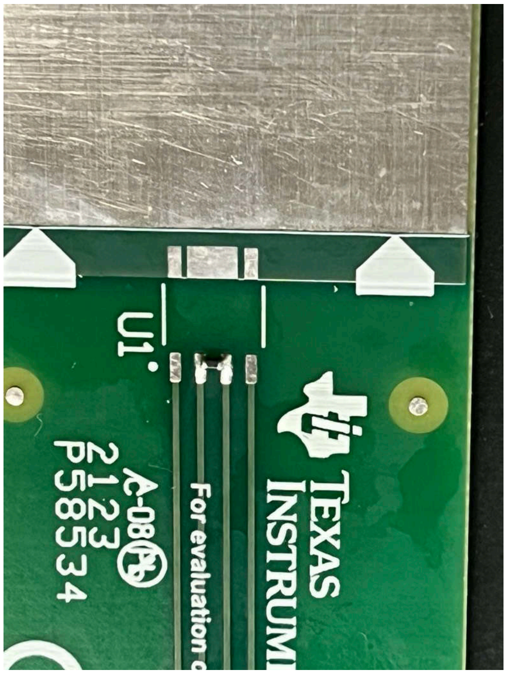

Figure 2-7. NTC Soldered onto Test PCB, Across Minimum Clearance

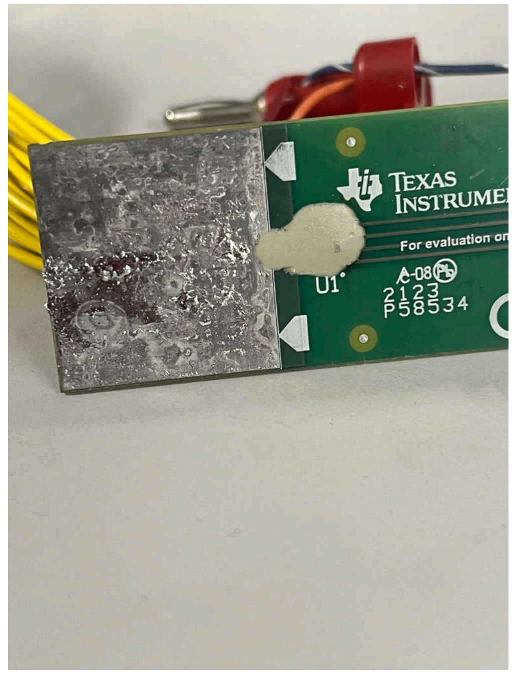

Figure 2-8. NTC with Cured Thermal Epoxy

2.5 Step 5: Testing Each PCB Configuration

To begin the test, 4 PCBs were assembled: 2 with ISOTMP35s, and 2 with NTCs (TSM0A103F34D1RZ). This particular NTC has a 1% temperature accuracy, and has a 0402 sized footprint.

Once all four PCBs were tested, thermal epoxy was applied to the NTC boards and then cured to thermally couple the NTCs to the copper pad. Once the thermal epoxy finished curing, those boards were then tested as well.

2.6 Test Results

After running all three tests on two boards each, the results were averaged together for each test. The results show that ISOTMP35 has a significantly faster temperature response time compared to either NTC option, with an average response time of 3.127 seconds. This is a factor of 10x better than even the NTC with thermal epoxy. Also worth noting that despite the NTC being in a much smaller package (which can provide a lower thermal mass and hence better thermal response time), the much larger ISOTMP35 is much faster.

ISOTMP35 achieves an average final temperature of 72°C. In this experiment, it is not able to achieve 75°C because the ISOTMP35 is fully exposed to the air during the test, which is 25°C. The ISOTMP35 is thermally coupled to the copper pad, but the cooler air temperature still drags the final achievable final temperature. This is still a significant improvement over an NTC, which was not able to exceed 66°C even with thermal epoxy.

Table 2-1. Response Time and Final Temperature Achieved Summary

DUT	Temp Response Time #1 (seconds)	Temp Response Time #2 (seconds)	AVG temp response time (seconds)	Final achieved temperature #1 (°C)	Final achieved temperature #2 (°C)	AVG final achieved temperature (°C)
ISOTMP35	3.1s	3.1s	3.1s	72.2°C	71.9°C	72.1°C
NTC no epoxy	74.9s	81.6s	78.3s	61.7°C	62.5°C	62.1°C
NTC with epoxy	47.2s	48.3s	47.8s	65.8°C	63.9°C	64.9°C

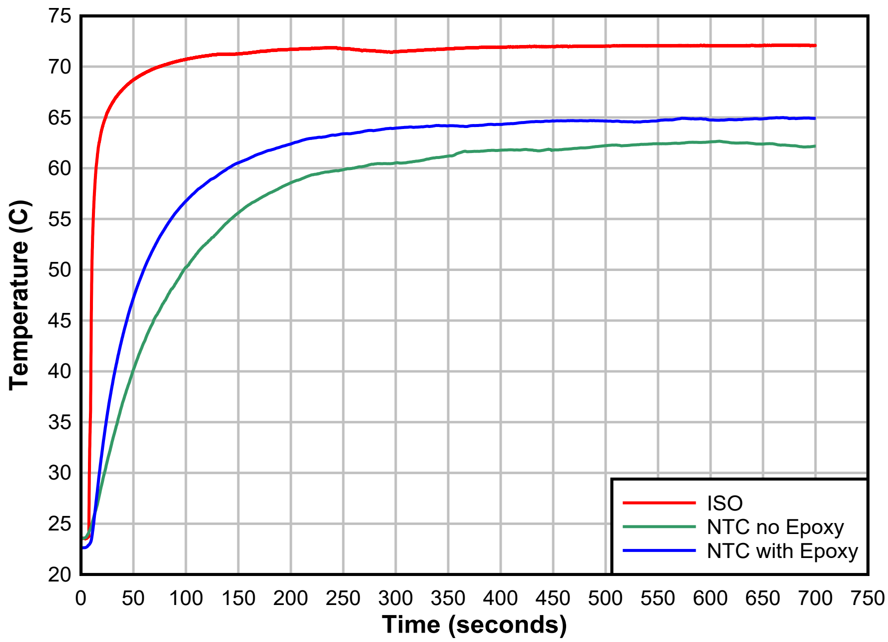

Figure 2-9. Temperature Response Time Results

3 Summary

The ISOTMP35 offers a significantly improved temperature response time over an NTC design. Having a faster response time coupled with a more accurate final temperature has several benefits for a customer. Safety can be improved using ISOTMP35, because ISOTMP35 can get much closer to the correct final temperature. This means that if an over temperature event occurred, having an NTC design that reads too low can miss a critical temperature event. A faster response time also means system lifetime may increase, since it will be exposed to an over temperature situation for a much shorter amount of time. In addition, a more accurate final value means that engineers can spend less time on thermal modeling. When using a non-isolated NTC that requires heat to travel across FR4, that heat transfer may need to be modeled and compensated for in software if the temperature drop off is not acceptable. However, when using ISOTMP35 in direct contact with the high voltage heat source, that modeling time is either not necessary or significantly reduced.

4 References

- Texas Instruments, *ISOTMP35 ±1.2°C, 3-kVRMS Isolated Temperature Sensor With Analog Output With < 2 Seconds Response Time and 500VRMS Working Voltage*, product page
- Texas Instruments, *ISOTMP35-Q1 Automotive ±1.5°C, 3-kVRMS Isolated Temperature Sensor With Analog Output With < 2 Seconds Response Time and 500VRMS Working Voltage*, automotive grade product page