Final Report - USB-C Overheating Solution

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1. Abstract:

This project addresses the prevalent issue of USB-C overheating in Audio Technica's Bluetooth earphones, aiming to prevent material damage. The problem arises from debris such as dust creating resistive faults and dangerous temperature spikes without increased current to the earphone battery.

Our approach focuses on reducing overheating risks and informing users about danger when an excess heat threshold is reached. Once a heat threshold is reached, the system lowers the temperature of the device while providing a visual warning system. Anticipated benefits include increased customer satisfaction, improved product longevity, and an increased reputation for Audio Technica due to the competitive market edge of our solution, which is guaranteed by researching competitors' patents for similar products. The research plan involves studying charging case technology, analyzing market competition, and searching for proprietary patents.

After conducting research and creating a comprehensive plan for a prototype, pending testing and experimentation will explore solutions, such as thermal sensors, op-amps, transistors, and LED indicators, to prevent overheating. This concise plan aims to deliver an effective solution, ensuring device safety, customer satisfaction, and enhancing Audio Technica's competitive position.

2. Methodology

Our team will develop a solution with the following problem statement: Our team aims to provide a solution that detects the heat generation from USB-C overheating scenarios and thus protects the device or employs a proactive measure to prevent the overheating. Using this problem statement, we will extract a list of constraints, objectives, and functions. From a morph chart of functions and means, our team will formulate design alternatives. A best of class chart with metrics will be used to evaluate the design alternatives and help the team choose a final design. Each component is detailed below.

3. Constraints

The team used the constraints to reject design alternatives that violated any constraints.
The constraints are listed in Table 1.

Table 1: A list of the constraints and the description of each constraint.

Constraint	Description
No damage to current device	Our solution should not cause any damage to the structure of functionality of Audio Technicas current devices

No safety threat	Our solution should not pose any safety risks to the health and well being of users
Be compatible with USB-C charging cases	Our solution must be compatible with USB-C type charging cases since this is the method that Audio Technica uses.

4 Objectives

The objectives are the desired attributes and features that a design alternative should possess. Ideally, the final prototype would perform well in all the objectives. The objectives are listed in Table 2.

Table 2: A list of the objective categories and the objectives that fall into each category.

Objective Category	Objectives
Design has a low cost to manufacture	1. Components are widely available. 2. Solution can be manufactured quickly. 3. Solution manufacturing has automation potential. 4. Manufacturing instructions are simple.
Design works with general USB-C charging & temperature conditions	1. Solution is effective under standard USB-C conditions (voltage, current, etc.). 2. Solution is effective under edge USB-C conditions (high temperature, etc). 3. Solution is universaly accepted by USB-C components, e.g. USB-C pins.
Design fits into the existing product	1. Design does not require a change with the current headphone casing. 2. Components are organized to optimize space. 3. Unnecessary parts are not included. 4. Design does not interfere with existing product functionalities, e.g. charging, comfort, etc.

5 Functions and Means:

The functions that the final product had to perform were put into a list (See Table 3).

Table 3: The functions for the final prototype.

Functions
Detects When Temperature Exceeds Thresholds
Cools Device When Temperature Exceeds Thresholds
Alerts User When Temperature Exceeds Thresholds

The functions and the means to achieve the functions were put into a morph chart, shown in Table 4. Our team used this morph chart to formulate design alternatives.

Table 4: The morph chart of the functions and means.

Functions	Means			
Detects When Temperature Exceeds Thresholds	Thermistor in analog circuit	Solid State temperature sensor in analog circuit	Thermocouple in analog circuit	Microcontroller with temperature sensor in digital circuit
Cools Device When Temperature Exceeds Thresholds	Passive cooling by stopping current, Hysteresis	Passive cooling by reducing current with microcontroller	Electronic fan in analog/digital circuit	Thermoelectric cooler in analog/digital circuit
Alerts User When Temperature Exceeds Thresholds	LED: Either flashing, completely, or multiple LEDs	Audio alert	Vibration	Sends SMS alert/Bluetooth signal to user

Design Alternatives:
Our team devised three design alternatives to prevent material damage to USB Type C overheating. We describe these in the next sections.

Design Alternative 1
The first design alternative uses a solid state temperature sensor to measure the temperature of the case as well as an op amp acting as a comparator, another op amp acting as an inverting buffer, transistors, LEDs, and resistors. This design measures the temperature of the printed circuit board immediately next to the charging circuit and by effectively choosing resistors, will stop charging the device using the transistors when the temperature gets too high. When charging is disabled, a LED notifying the user that there is a problem will turn on.

Design Alternative 2
The second design alternative is very similar to the first alternative, however the solid state temperature sensor has been replaced by a thermistor. This design measures the temperature of the case directly which gives a more accurate reading of when the case may melt. Additionally this design incorporates a hysteresis circuit which allows the case to have a chance to cool below its glass transition temperature before resuming charging. This prevents unnecessary load on the charging circuit as it prevents the battery from being connected and disconnected constantly as the temperature hovers around the glass transition temperature. Similar to before, when charging is disabled, a LED will turn on letting users know that the port is not clean.

Design Alternative 3
The third design alternative proposes the utilization of a microcontroller such as an ESP32 to handle the logic within the design as opposed to the analog circuitry of the other solutions. Instead of using an external temperature sensor, design alternative 3 uses the internal temperature sensor of the microcontroller to monitor the temperature of the circuit. Not only does this solution greatly reduce the number of components required inside the device, however it allows for greater interaction with the user. For example, the integrated WiFi circuitry of the ESP32 can allow for push notifications to be sent to the user's phone if the device overheats. Additionally we could make the LED change colors or flash when there is an issue. Unfortunately, the ESP32 chip does get very warm during use which would cause erroneous reading and waste power when the headphones are not charging.

16 Best of Class Chart

Objectives	Solid State w/ Hysteresis	Thermistor w/ Hysteresis	Microcontroller
Minimal manufacturing time, cost, complexity, & sourceability	1	3	2
Functional under standard & extreme conditions			
Fits into existing product	2	1	3
Doesn't interfere with product functionality			3 - Generates heat
Effectively prevents damage from overheating	2.5	2.5	1

Final Prototype

Based on feedback from Audio Technica and from peers, the USB-C charger overheating team has decided to use a solid state temperature sensor combined with a comparator hysteresis circuit to detect an excessively hot USB-C charger. Once the sensor has detected a temperature exceeding the a high temperature limit that can be chosen arbitrarily, the charger will shut off and an LED light will turn on to alert the user that charging has stopped. This occurs at the upper temperature boundary of the hysteresis circuit. Once the charger cools to the lower temperature boundary of the hysteresis circuit which can be chosen arbitrarily, charging will restart and the LED will turn off.

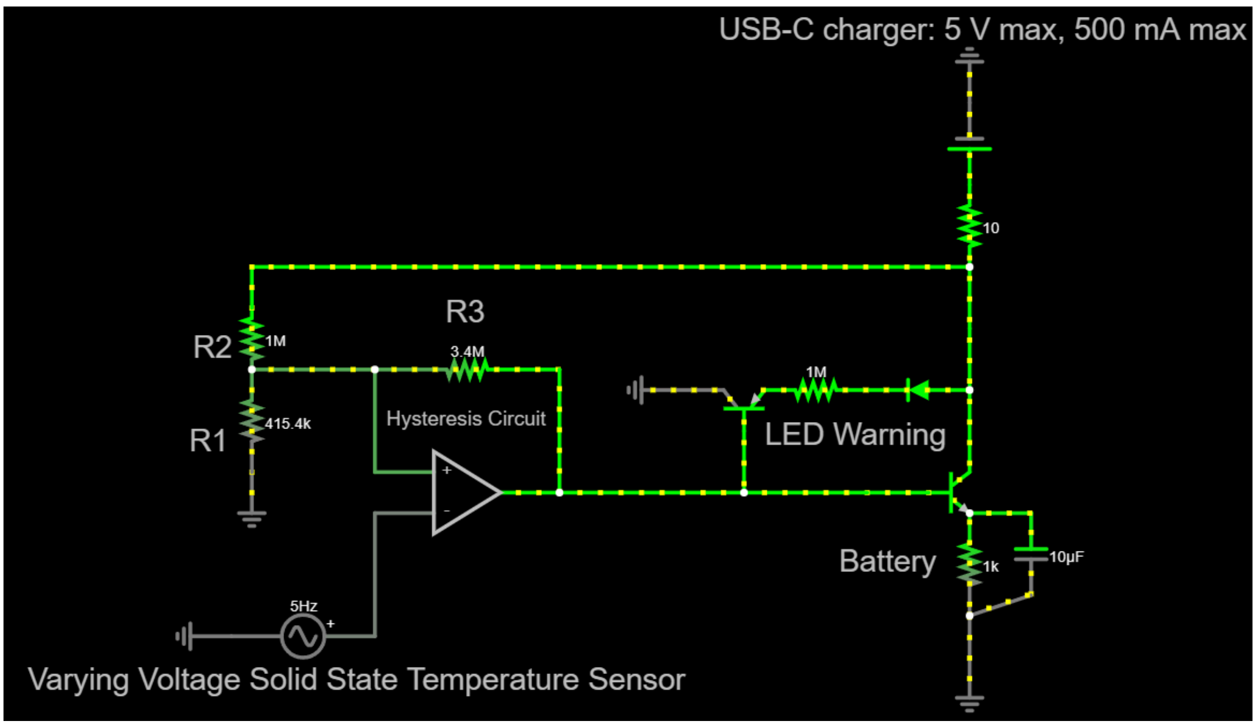
Some of the reasons that we decided to go with a solid state temperature sensor as opposed to a thermistor is because thermistors are not universally consistent across different models. In comparison, all solid state temperature sensors follow roughly the same linear relationship between voltage and temperature. This means that if a thermistor goes out of production from the manufacturer, then the entire circuit will need to be recalibrated and redesigned. Additionally, over time, solid state temperatures sensors are more consistently able to read temperatures which will ensure longevity of the product.

Because the upper and lower temperature limits in the hysteresis circuit are arbitrarily chosen, this circuit design can be easily modified in order to appeal to any temperature limit desired. The process for modifying the circuit for any desired temperature is given in the next section, the procedures for designing the circuit.

Procedures for Designing Final Prototype

The circuit for the final prototype is given in the Figure Below. The components of the the circuit are listed below:

- PNP Transistor
- NPN Transistor
- Solid State Variable Resistor (MCP9701)
- Op-Amp (MCP6002)
- One 1MΩ resistor for decreasing current through the LED
- Three resistors, R_1, R_2, and R_3



Circuit diagram of the hysteresis circuit modeled in Falstad, link below: https://tinyurl.com/28lrda8h.

In the circuit above, the resistor values R_1, R_2, and R_3 control the upper and lower limits of the hysteresis circuit for any arbitrarily chosen upper and lower temperature limit. For testing purposes, the upper and lower temperatures were chosen to be 70℃ and 50℃ respectively. For the temperature sensor that we used, those temperatures match up to 1.75 V and 1.35 V respectively (See Figure below). As discussed previously, these temperatures can be chosen arbitrarily (from the range of -10℃ to 125℃ so that the linear approximation is accurate), thus allowing the circuit to be highly flexible for any temperature situation Audio Technica requires.

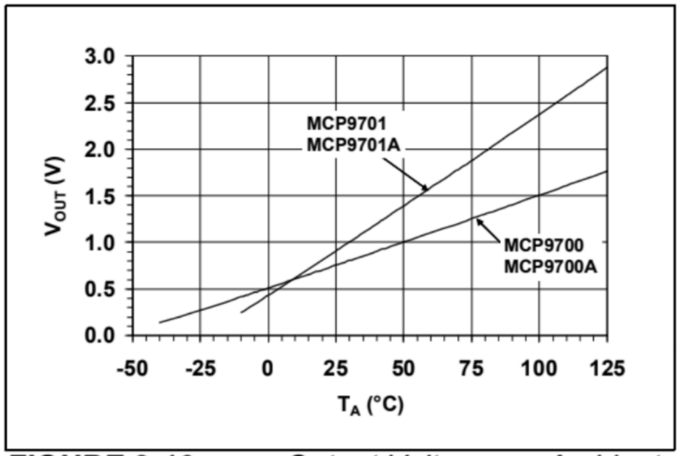


FIGURE 2-16: *Output Voltage vs. Ambient Temperature.*

Graph for the voltage threshold for a given temperature. https://drive.google.com/file/d/1ZZ7An-GFcWQ5SsR5wrQlyf-qWexbjHdo/view The important line is the top line for the MCP9701 temperature sensor, which is the one used in the circuit. For our testing purposes, we chose a high voltage of 70 C, or 1.75 V, and a low voltage of 50 C, or 1.35 V.

Based on the high and low voltage chosen, the corresponding resistors values required to achieve these voltages are calculated based on the following equations [Comparator with Hysteresis Reference Design (ti.com)]. As a note, the source voltage, V_S , is retrieved from the USB-C source voltage and is 5 Volts. The upper temperature voltage is represented by V_H , and the lower temperature voltage is represented by V_L.

$$R_2 = Free\ Variable\ (Set\ to\ 1M\Omega\ for\ Default)$$

$$R_1 = R_2 \frac{V_L}{V_S - V_H}$$

$$R_3 = R_2 \frac{V_L}{V_H - V_L}$$

For the 50 C and 70 C temperature limits chosen for testing purposes, the corresponding resistor values are R_1 = 415.4 kΩ , R_2 = 1 MΩ, and R_3 = 3.375 MΩ. We tested this design, and this is described in the next section.

Tests Performed on Final Prototype

1. Heating up with heat gun and verifying current load drops at desired temperature
2. Cooling down with ice cube and verifying current load increases at desired temperature
3. Heating up with heat gun and and verifying LED turns on at desired temperature
4. Cooling down with ice cube and verifying LED turns off at desired temperature

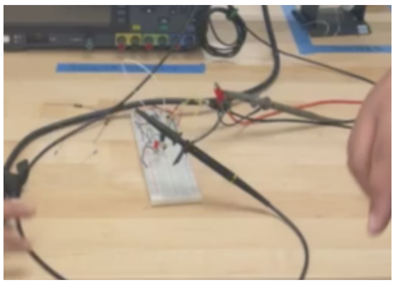
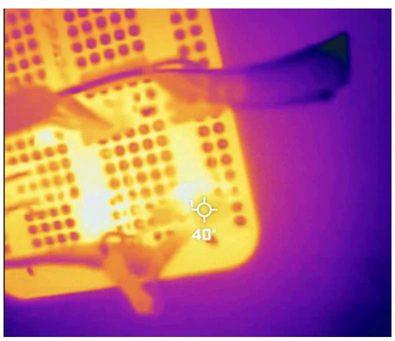
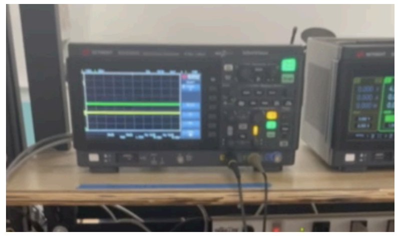
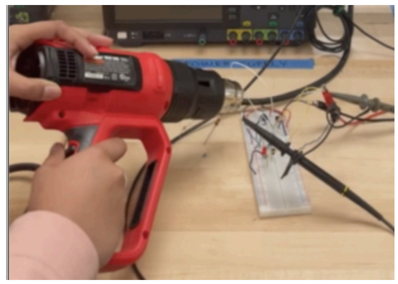
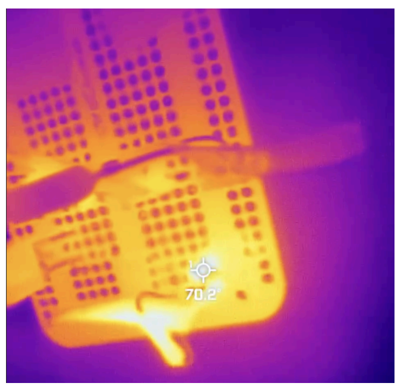
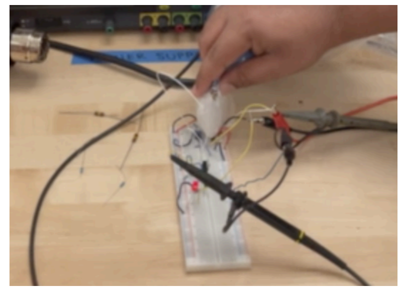
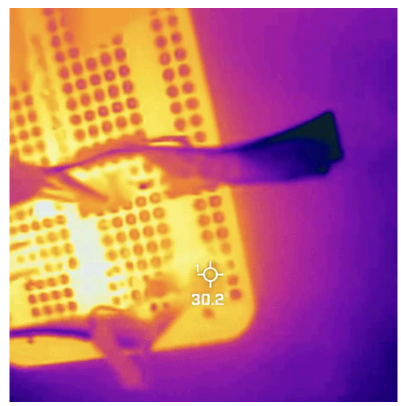
The circuit simulates a battery by using a 1000 ohm resistor. Because the voltage into the system is 5V, we expect to see a current draw of 5mA from our power supply when the NPN charging transistor is closed and allowing current to flow. The other transistor is a PNP connected to an LED which will turn on when the charging transistor turns off. The transistors get their Base signal from an op-amp comparator with hysteresis which allows the high temperature off point and the low temperature on point to be different from each other. To verify this circuitry worked as intended. We first used a heat gun to heat up the device and then used a FLIR infrared camera to monitor the temperature of the sensor.

Test 1. We connected the power supply to the circuit. Upon turning on the power supply, it drew 5mA as expected. We then heated the circuit to 70C, the high temperature cutoff point. At this point, the current draw dropped to 1mA, as the LED and other components were still being powered showing a successful test.

Test 2. After completing test 1. We applied an ice cube to the temperature sensor to cool it down. Upon the temperature sensor reaching 30C, the low temperature cutoff point, the current went back up to 5 mA indicating a successful test.

Test 3. We connected the power supply to the circuit. Upon turning on the power supply, The LED was turned off as designed. We then heated the circuit to 70C, the high temperature cutoff point. At this point, the LED turned on as designed, indicating a successful test.

Test 3. After completing test 4. We applied an ice cube to the temperature sensor to cool it down. Upon the temperature sensor reaching 30C, the low temperature cutoff point, LED turned back off as desired in the system.

Steady State	Heating	Cooling
  	  	  

Limitations for Final Prototype

Other than size and cost limitations which are discussed in the next section, the largest limitation of the prototype is the difficulty with which it is to verify it is working. To try to overcome this limitation, the team performed several tests in order to simulate USB-C overheating and the circuit working. To do this, the team put together the most head-producing pieces of scraps that would get caught in a USB-C charger: lint, salt, a small amount of water, some food (hot sauce), and small bits of aluminum to hopefully divert electricity from the desired source. The team combined this together and put it in a USB-C charger in an attempt to generate heat. These items are imaged in the image below.

Image of the items that were placed in a USB-C charger in an attempt to generate heat.

However, this configuration was unsuccessful in generating heat, and the team detected no temperature change in the charger after 10 minutes of charging with this in the charging port. Instead, to test the circuit, the team manually heated the circuit with a heat gun and then allowed it to cool down several times while using a visual camera to track when the LED turned on as well as a thermal camera to track the temperature of the temperature sensor. The team then synced and overlaid these two videos together. As can be seen in the videos, the LED turns on at approximately 75 C^{o}, and then turns off at approximately 50 C^{o}. This video can be seen at the following link, which is a google drive video file that is accessible to all. These multiple cycles of heating and cooling is strong evidence that the circuit works. Furthermore, the team has also tested independently that the charging stops when the LED is turned on.

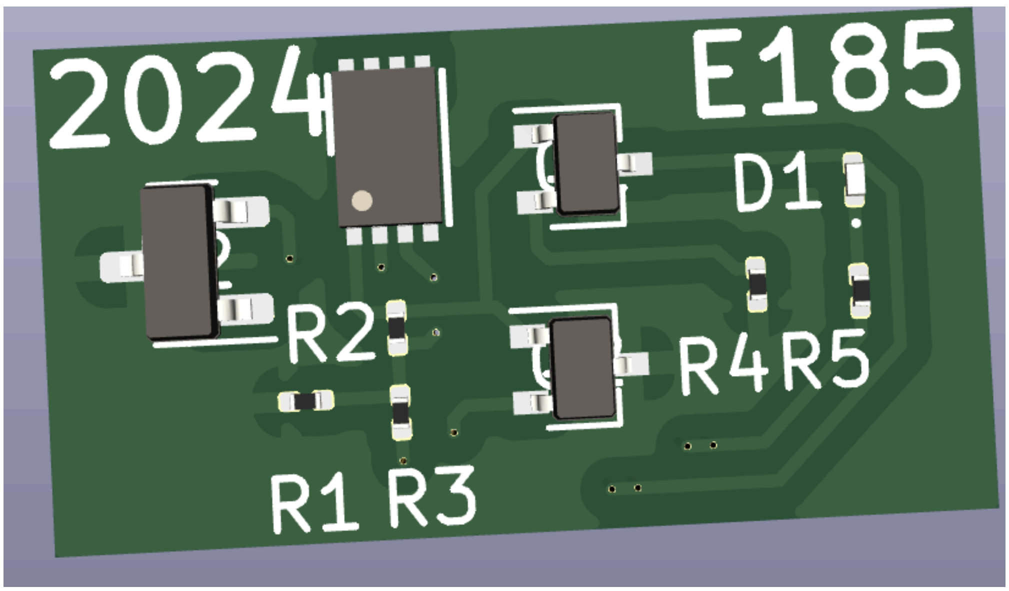
https://drive.google.com/file/d/16G91q4tQUhkpe-3u2gXXNn1kdhkUKh_t/view?usp=sharing

Link to the Synced Video for Testing

Other than testing if the circuit works, the other main limitation is ensuring that the temperature sensor is measuring the correct temperature. In other words, as Audio Technica implements this design into their products, they should take care to ensure that the temperature sensor is installed next to where heat is generated to ensure the temperature sensor is measuring the highest temperature on the device.

Design of Circuit for Mass Production

In order for Audio Technica to mass produce this circuit, several changes need to be made from the team's prototype. These design changes are intended to minimize the cost and size of the circuit, and these changes are outlined below.



Link to KiCad files:
https://drive.google.com/file/d/1cXUQHLe97BbodocKOpbqNIft7_F7OvvA/view?usp=sharing

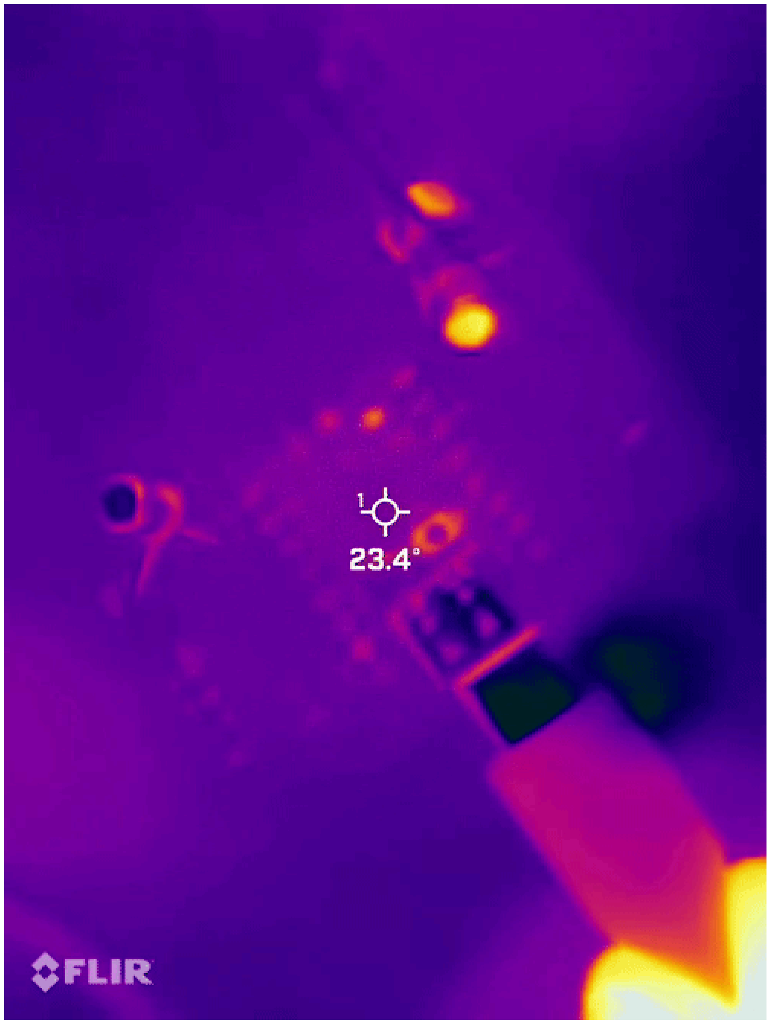
All resistors and the LED use the smallest SMD package available: 0201 at 0.6mm by 0.3mm. The temperature sensor, op-amp and transistors use the smallest available package. The entire board itself is about 18.5 mm by 9 mm which is likely larger than a final integrated solution would be. Some opportunities for space savings include, reusing an already existing op-amp on the board to save on adding an additional component and generally placing components closer to each other on the board. One important component placement consideration should be the temperature sensor. The temperature sensor should be placed as close to the USB port as possible to make sure that the temperature can most accurately be read from the device.

The total price of components for the final solution, assuming 150,000 devices would be manufactured is about 68 cents. 150,000 is the quantity required to ensure all components are ordered at their cheapest price. The PCB that already exists inside of the headphones would need to be modified. The cost of manufacturing the modified PCB would likely be negligible.

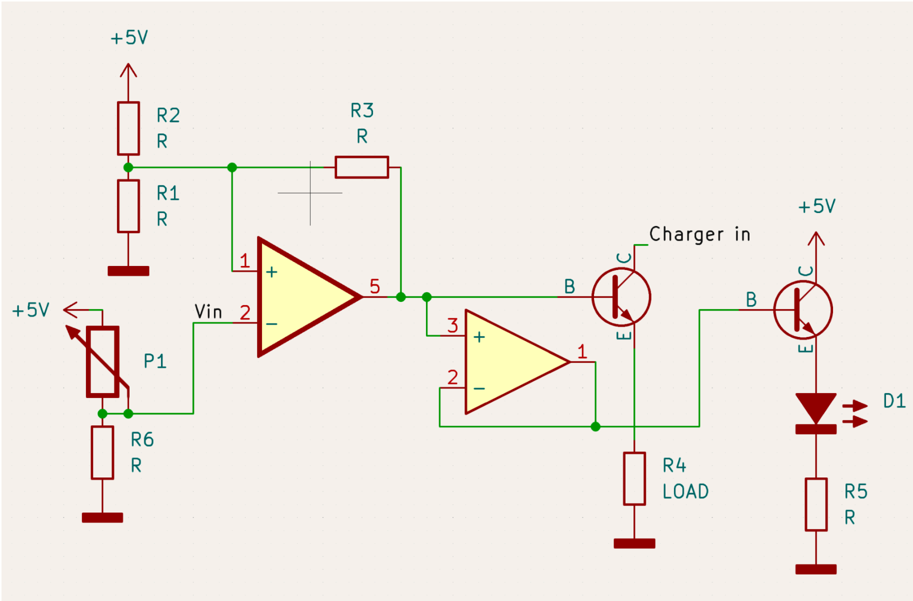
Component	Price per unit	Min order quantity
430kohm	0.0022	100000
1mohm	0.00198	105000
3.3mohm	0.0034	105000
1kohm	0.00175	100,000
MCP6002	0.22	3300
LED	0.093	100000
Temp	0.22	3000
NPN	0.1125	75,000
PNP	0.02757	150000
Total:	0.6824	

The link to the digikey shopping cart where specific component selections can be found is here. https://www.digikey.com/short/04d0pzr8

References and Extra Information



The above image is an experiment the team did where we imaged a microcontroller with a thermal camera as we input power to the device with a USB-C cable. As shown by the short video, the components on the microcontroller generate a significant amount of heat. So, using a microcontroller in our solution would not be optimal due to the heat generated.



A Hysteresis circuit. Hysteresis is the process by which, if an upper threshold temperature is met, such as 100º C the circuit will turn off the current in order to cool the device. Then, the current will turn on when a lower temperature threshold is met, such as 90º C. This is done in order to prevent the current from flickering on and off.

Other References:

Burn Exposure Chat: Can use this as reference for how hot an object can be and for how long before causing serious injury

Glass Transition temperature of Hard Polycarbonate, which is what is used in AirPod Cases, is 85 C: Glass Transition Temperature (Tg) of Plastics - Definition & Values (specialchem.com