Emergency Thermal Balance

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Problem Definition and Background

Heat stroke is a life-threatening condition that occurs when the body overheats, often due to overexertion in high temperatures, and can lead to severe organ damage or death if not treated quickly. Symptoms include a body temperature above 103°F, red and dry skin, rapid pulse, confusion, and unconsciousness. Immediate treatment involves cooling the body rapidly through methods such as cold baths, ice packs, or fans, and calling emergency services [1]. Crucially, the patient’s body temperature should be lowered to around 101°F as quickly as possible to prevent lasting damage [2]. However, these methods may not always be accessible or effective in remote or resource-limited environments. This highlights the urgent need for a standardized, portable, and reliable treatment method, which is the goal of the Emergency Thermal Balance project.

Objectives

- Design and Build a System that Reduces the Wearer’s Body Temperature from Dangerously High Temperatures to Safe Temperatures within Thirty Minutes
- Build the System to be User-Friendly and Completely Self-Contained, Requiring No External Power Source
- Ensure That the System is Safe to Use and Highly Portable

Needs Statement

The Emergency Thermal Balance must provide immediate, effective cooling by removing unnecessary clothing and addressing environmental factors, regardless of location or response time. Continuous monitoring of vitals is essential to ensure safety, while minimizing shivering to avoid counteracting cooling. Rapid transfer to professional medical care is critical to prevent complications from heat stroke.

Design Alternatives

Three main cooling system alternatives were considered: a liquid refrigeration system, a thermoelectric (Peltier) conduction system, and an air convection system.

The Liquid Refrigeration Design would utilize a traditional refrigeration cycle with a liquid refrigerant circulated through tubes in contact with the wearer. While effective and proven (similar to NASA suits), it was costly, power-intensive, and raised safety concerns.

The Peltier cooling system proposed embedding thermoelectric chips into a garment, cooling through direct skin contact. This method was simple but limited in coverage, required tight clothing, and could risk overheating from the chips' hot sides.

The air convection system cooled air using a gas refrigeration cycle and delivered it to the patient through tubes. It offered widespread cooling but struggled with energy efficiency and portability.

Each alternative had trade-offs, with the air convection system showing the most promise if redesigned to better retain cold air.

Design Requirements

The Emergency Thermal Balance project must be completed by May 2025 within a budget of $1850, including a required full use of a $1450 NASA grant. The system must rapidly cool a patient within 30 minutes, lowering their core temperature to 101–102°F without exposing them to hazardous materials. It must be portable, lightweight,fully self-contained with an internal battery capable of immediate operation, and designed for safe, easy handling. The design follows standards to ensure safety, reliability, and performance:

- **Thermoelectric cooling**: IEC 60738-1:2022.
- **Fan performance**: ISO 5801:2017.
- **Battery function and safety**: IEC 60896, IEC 60335-2-29:2016.
- **Electrical wiring**: IEC 60335-1:2020, UL 1977.
- **3D printed plastics strength**: ASTM D638, ASTM D790, ASTM D256.
- **Plastic tubing durability**: ASTM D790, ASTM D1598.
- **Power regulation**: IEC 61558 for buck converters.
- **Heatsink thermal performance**: JESD51-2 and JESD51-6.

Final Design

The final iteration (see bottom right of page) of the design consists of four main subsystems:

1. **Cooling Subsystem (seen below)**

The cooling subsystem is a thin chamber lined with the cold sides of 20 peltier devices, each attached to an aluminum heatsink with fins parallel to the airflow. Air is passed into this chamber using an 80mm x 80mm fan and exits through two tubes attach to the garment worn by the patient.

1. **Heat Extraction Subsystem (seen below)**

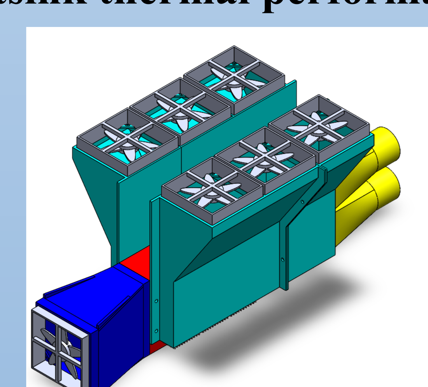
The heat extraction subsystem consists of 20 aluminum heatsinks attached to the hot side of each peltier device, and 6 box fans blowing funneled air over these heatsinks to remove more heat.

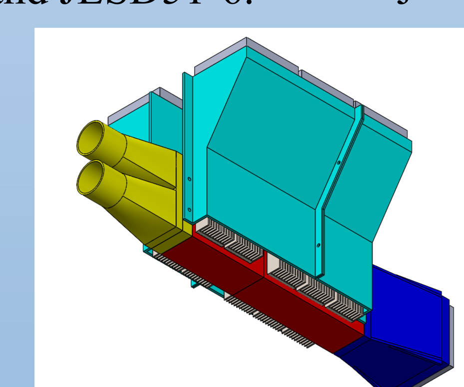
1. **Power Regulation Subsystem**

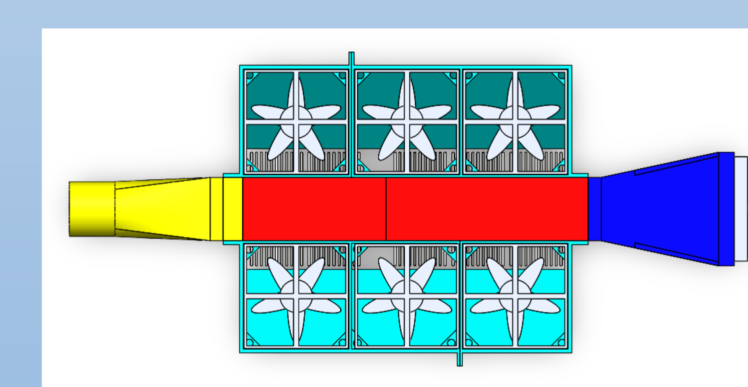
The power regulation portion of the system consists of 5 buck converters. These converters are each hooked up to the battery in parallel. The buck converters take in current at 12 V and output charge at a set current and potential to the peltier devices (4V and 2A in this case).

1. **Garment Cooling Interface Subsystem**

The cooled air flows through tubes to connect to a thin elastic jacket via flow collars. The user wears the jacket.







Conclusion

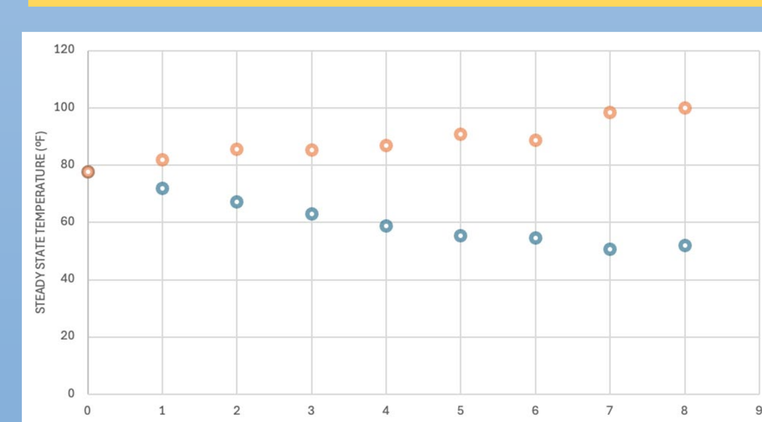
Based off the tests of the full system’s performance, the Emergency Thermal Balance Project shows promise. The Emergency Thermal Balance was able to decrease a wearer’s axillary skin temperature by 9.8ºF, the exit temperature by 8.5ºF, and the garment temperature by 3.3ºF over the course of 10 minutes. This data indicates this system is capable of producing a colder enclosed environment inside the garment relative to the ambient temperature. However, none of these metrics measure core temperature, which is what needs to be lowered by from 103+ºF to 101-102ºF. Also, it cannot be said whether the system would perform more or less effectively in the extreme heat of heat-stroke inducing temperatures, as such conditions are not readily available. Whether, the final design would work requires more invasive and conditional testing, especially tracking core temperature over a thirty minute period. Further improvements to the heat extraction subsystem, more efficient Peltier devices, and reducing head loss caused by the tubing duct would increase the final system’s effectiveness. In summation, the system feasibly reduces body temperature, but since the relationship between skin and core temperature is nonlinear and thus a direct conclusion may not be possible at this stage.

References

[1] Mayo Clinic, “heat stroke - Symptoms and causes,” *Mayo Clinic*, Jun. 25, 2022. https://www.mayoclinic.org/diseases-conditions/heat-stroke/symptoms-causes/syc-20353581.

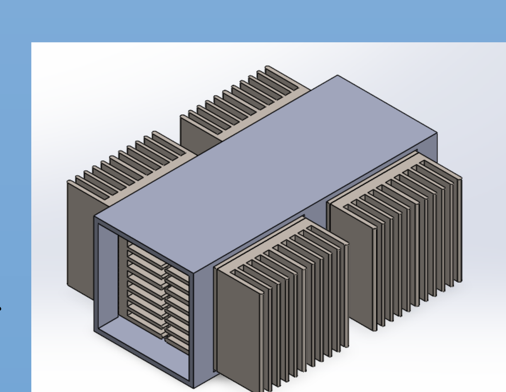
[2] Mississippi State Department of Health, “Heat Exhaustion and Heat Stroke,” 2024. https://msdh.ms.gov/page/43 (accessed Dec. 09, 2024).

Design Evaluation and Iterative Process

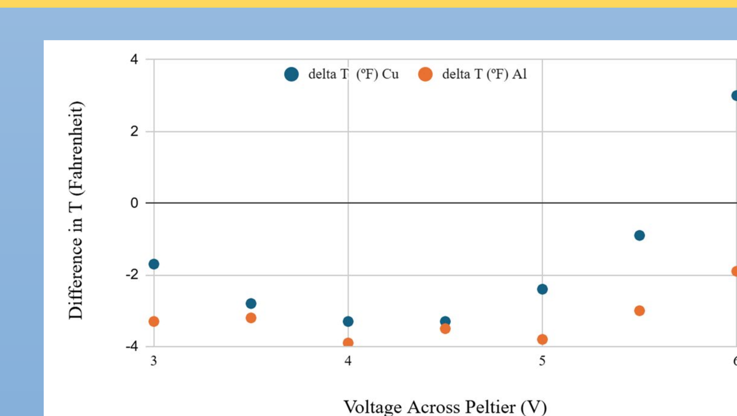


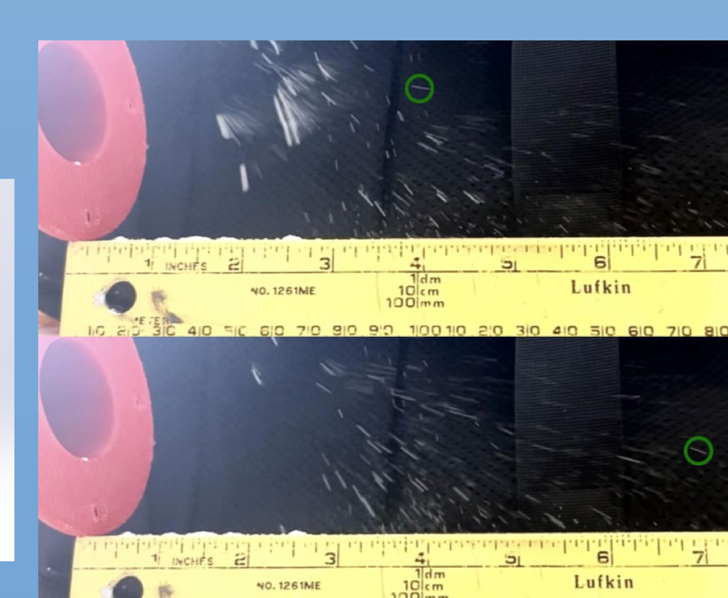
EXP.1: The difference in temperature between the cold side and the hot side of the peltier device at steady state is shown in the plot (left). The test system performed as expected and illustrated not only the necessity for heatsinks, but the validity of the thermoelectric devices integration into the design plan moving forward.

EXP.2: A CAD model of the miniature system is shown (right) in the experiment fans were blown over each outer heat sink and one through the middle. The created air temperature difference for a small-scale version of the system varied between -3.2 and -3.9 ºF. The miniature version of the system is a proof-of-concept that a significant negative temperature difference will be created.



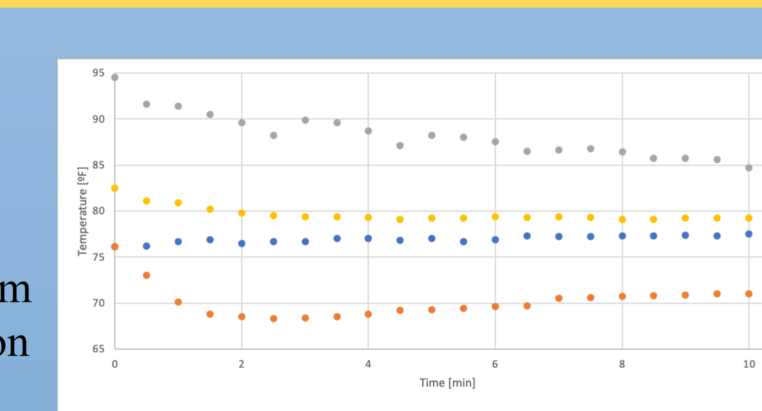
EXP.3: Likely due to the geometry of the copper and aluminum heatsinks, the aluminum heatsinks created a larger temperature difference than the copper heatsinks despite copper’s higher heat capacity and heat transfer coefficient as seen in the plot (right).





EXP.4: Using video analysis of flour particles aligned with a ruler, airflow velocity was approximated by finding the amount of time that had passed between two frames and the distance a flour particle had traveled. The flow rate was able to be calculated by finding the cross-sectional area. After 10 trials were completed, the flow rate of air exiting the system was 0.1484 +/- 0.0215 ft³/s inlet airflow is claimed to be .983 ft³/s.

EXP.5: Full System Performance Evaluation: The final system was analyzed on three metrics.



These metrics are: axillary skin temperature, exit chute temperature, and garment temperature over the course of 10 minutes. Axillary skin temperature decreased by 9.8ºF from 94.5ºF to 84.7ºF, the maximum temperature difference between exit and ambient air was 8.5ºF where ambient was 77ºF and exit was 68.5ºF, and garment temperature decreased by 3.3ºF from 82.5ºF to 79.2ºF. Axillary temperature was used because it is an area of the body that tends to radiate more heat.

Acknowledgements

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