Thermoelectrically Cooling Large Areas with Phase Change Materials Proposal

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Introduction

Air conditioning units (AC) are used to cool down or heat up rooms in areas where the weather varies widely from extremes of hot or cold. However, there is a significant energy and environmental cost of using modern AC units. Modern air conditioners use metal pipes that transfer liquid coolant through homes. In modern AC units, liquid coolant in these metal pipes collects heat and turns into a gas form, which travels through home pipes into a compressor cooling the gas back into liquid. However, little leaks occur in these pipes. R-410A, used in modern systems, is the liquid coolant composed of a mixture of HFC liquids. Even though R-410 has less global warming potential than predecessors, it still, when leaked out as a gas, negatively increases the amount of toxic greenhouse gasses in the atmosphere. Most advice in articles are to repair AC systems, insulate houses better, and lower usage of AC, however these options aren't that practical for the majority of people as they cost money or risk discomfort. This is a global problem as global warming affects multiple countries such as Australia which had above-average temperatures this year (Global Climate Report, 2024) . Over 40% of greenhouse gas emissions and electricity in the U.S. spout from buildings with traditional air conditioning units with this toxic air conditioner coolant putting this liquid coolant as one of the major causes of increase in greenhouse gasses (Jakka 2024). A more feasible solution is to redesign how an AC system works, avoiding the usage of HFCs as coolants totally, lessening the greenhouse gas emissions by air conditioning. There are already methods of cooling without liquid coolant, however they are limited to being applicable in certain scenarios, or possess a very high electrical energy consumption. My research will test a combination of two methods of cooling using phase change materials with a thermoelectric system, switching on and off to cool an area at efficient energy usage.

Critical Literature Review

Over 40% of greenhouse gas emissions and electricity in the U.S. spout from buildings with traditional air conditioning units with the toxic air conditioner coolant, which has high GWP (Global Warming Potential) (Jakka 2024). This is because air coolant is a liquid made out of materials like HCFCs, high containers of carbon, that deplete the ozone layer of the atmosphere. Researchers are currently looking into other forms of air coolant for typical air conditioning systems; however, because coolants are meant to be stable to avoid leakage within a system and to continue being circulated without breaking down and so, they reach the upper atmosphere and release chemicals like chlorine that break down the ozone layer. This poses the question of if a room can be cooled down using a different air conditioning method rather than a standard system that uses coolant, effectively avoiding the harmful by-products of greenhouse gasses. This literature review covers if thermoelectric cooling devices, a cooling method that does not use coolant, can be designed more efficiently to be practical for larger scale cooling areas such as an apartment.

There are two largely researched areas of systems that do not use refrigerant coolant as a system for cooling: desiccant systems and thermoelectric systems. Desiccant systems use a conditioner (desiccant), a chemical that can absorb moisture within air. By getting airflow through this chemical, the desiccant can remove humidity from the air, and when the desiccant gets diluted, it regenerates through the process of heating where the desiccant releases the moisture outside (Jakka 2024). Because rooms have lower humidity levels with this system, it is easier to cool down an area with less power. Although this method of cooling is environmentally friendly, these systems would not be effective in areas with drier climates and hot weather since they rely on removing humidity, not cooling air temperature directly. On the analysis of desiccant technologies, Jakka explains how the system uses a combined heat power element, CHP, a system where as gas is input, the production of heat and electricity is output which could make other cooling systems that use both electricity and heat more efficient, being environmentally friendly if biogas, a renewable natural gas, is used.

The next environmentally friendly systems are thermoelectric devices TEs that cool areas using the Peltier effect. The Peltier effect relies on using electricity to move heat on one side of a plate, making the other side freezing cold, shown by Fig 1. By passing current through N (negative) and P (positive) type semiconductor materials in combination, electrons travel from one shell level to another, the change in movement from the shell levels causing heat on one side (Bell 2008). When electrons travel from a lower level to move to a higher level, they do not move around as much, while electrons traveling from a high level to a low level have room to move around more. This generates heat on one side of the plates where the electrons are moving more, while the other side is made cold due to the lack of movement. By utilizing this temperature difference on either side of the plates, an object or area can be cooled down or heated up with electricity by transferring the temperature difference to the air, usually using radiators, a heat absorbing object, with fans or water cooling.

TE coolers do not use harmful air coolant like traditional air conditioner systems, and unlike the desiccant systems, their efficiency is not based on the humidity of the area, making them a good system to implement for cooling. However, these systems use a lot of electrical energy and become less efficient when there is a large temperature difference on both sides of the plates (Zebarjadi 2023). For example, if the thermoelectric system is stationed where one side of the plate is very hot and the other plate is very cold, because in the hot side of the TE electrons are already in an excited state, there needs to be more current passed through the system to continue pushing electrons to that excited level, decreasing the efficiency heavily. Another defect is that if the TE reaches a state in which the temperature difference on either side of the cooler is minimal, little heat will be able to be absorbed from one side and output on the other side making the system ineffective. For this reason, TE coolers have a bad reputation for not being a viable way of cooling a large area (Technology Connections 2024). Researchers have been looking at better ways to improve TE cooling systems by finding better materials to make thermoelectric coolers out of to increase the electricity to heat efficiency, coefficient of performance COP, however, not many papers go over how to design a better overall system to disperse the energy transferred by these thermoelectric systems in a better manner to keep the TE cooler temperature difference little allowing the system to remain efficient, lowering electricity usage. Without getting into material science to improve the energy efficiency of thermoelectric systems in improving the electrical usage efficiency and temperature transfer to the air, there are two hypotheses that come to mind to improve these thermoelectric cooling systems.

One is to, like mentioned above, distribute the temperature better to the air, keeping the thermoelectric system at a slight temperature difference. When designing a thermoelectric system, Yuewu breaks down using math an explanation that keeping some sort of temperature difference on a thermoelectric cooling system is critical since the cooling system generates heat on one side of the plate not only using electricity but also by transferring heat from the colder plate to the hotter plate (Yuewu 2022). For this reason, a more heat-conductive material should be used on the hot side of the plate, distributing heat more quickly to the air, while a slightly less heat-conductive material should be used on the colder side of the plate to still keep absorption of heat high but also make sure that the temperature difference between the two sides does not hit a solid-state. By implementing this into a design, a more efficient cooling system would be developed. Methods of better heat absorption, such as using heat pipes with heat fins on the hot side of the plate, could transfer heat from the hot side of the plate to the air faster if paired with other conventional methods of dispersing this collected heat, through air or water cooling. Using air cooling on these heat fins is a more simple, and a less electricity-consuming process; however, it isn't as efficient as transferring heat as water cooling. Water cooling directly transfers heat to radiators to be dispersed. Systems like these have been tested before on smaller units like mini-fridges and proved to be efficient when cooled properly, proving that TE's do have potential to be suited for larger scale application. Another way to collect heat in one area of a room to make TE cooling more efficient is using PCMs (phase change materials), materials that change phases to absorb or release heat (Zormati 2023), something that hasn't been researched on yet. For example, water, a PCM, absorbs heat on the room side until it changes phase into ice, where it then releases some of this heat into the hot side. When the material is in a water state, the cooler does not have to use as much energy, having to keep running, to absorb heat from everywhere in the room instead of one targeted area. In addition, with a smart system to control the power usage of the system, the electricity efficiency could be improved.

The second hypothesis is to use an efficient thermoelectric generator to help supply the thermoelectric cooler with enough power to keep the cooler efficient naturally, which should take away from the massive load that Peltier coolers run on (since they run constantly). Thermoelectric generators utilize temperature differences on both sides of a TE to generate electricity using the Seebeck effect. When one side of a material is heated compared to the other colder side, excited electrons move from the heated side to the cold side and follow in a cycle that generates movement and therefore can be turned into electrical energy (Bell 2008). The same Peltier thermoelectric devices used for cooling are capable of using the Seebeck effect to generate electricity. As of now, thermoelectric generators are not that efficient since they require a constant temperature difference between both sides of the plates, and over time the temperature difference comes to a solid state. Researches such as Zebarjadi and Resciniti have talked about this from a material perspective of the conclusion that the ZT performance of the TE devices (Z representing the efficiency of the electricity generation of the material, T representing absolute temperature capacity) should be improved; however, thermoelectric systems can be improved by **directly** heating up one area of a plate and having another area cooler, which would constantly keep a temperature difference between both sides of the TE. By using a solar collector on one side of the TE and a freezing PCM material on the other side, such as ice well insulated on both sides, electricity should be able to constantly be generated naturally to help supply the thermoelectric cooler. Solar thermal collectors use solar energy to heat up liquid which can then be transferred to heat (Sheikhani 2018). If both of these systems are paired together, thermoelectric coolers may be viable to run on a larger scale. Solar thermal collectors can also be used by themselves if paired with some steam system to generate electricity as well. This system would have to use a well-implemented heat transfer system such as the mentioned earlier water cooling/heating or using heat pipes with fins to transfer heat properly.

To carry out experiments, testing can be performed as a scaled-down thermoelectric system like a mini-fridge with different variables, such as testing better cooling systems for distributing heat to the actual thermoelectric device (whether it be through water cooling or fan cooling) using different types of phase-change materials and/or testing the electricity output of a thermoelectric generator that uses a solar collector and ice for targeted temperature differences.

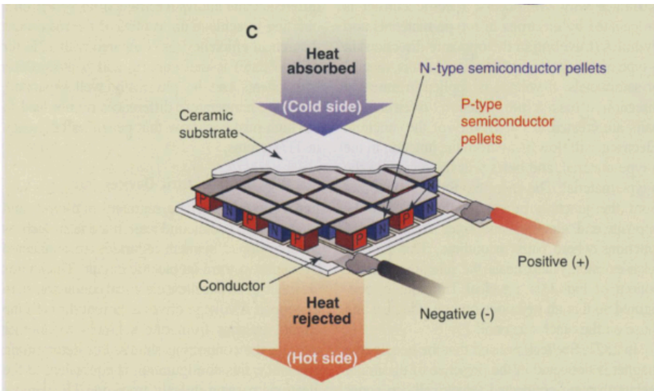


Fig. 1. TE heat engines. **(A)** When current is run across a TE junction, it heats or cools through the Peltier effect, depending on the direction of the current flow. **(B)** When heat flows across the junction, electrical current is generated through the Seebeck effect. **(C)** Practical TE generators connect large numbers of junctions in series to increase operating voltage and spread heat flow.

Fig. 1 (Belle 2008)

Research Design

Current thermoelectric coolers can drop the temperatures of minifridges by 32 degrees fahrenheit (18 Celcius) such as in the Koolatron Coca-Cola minifridge (Koolatron). This should be sufficient enough to cool a larger area, however peltier thermoelectric modules lose effectiveness in larger areas since it takes an inefficient amount of electrical energy to keep the peltier modules running while also yielding a very small temperature drop as the peltier modules are only reaching a small portion of the room.

To solve and model the problem of widespread heat, the design will collect heat in one area using airflow from room toward ice, the ice absorbing heat from the area, then cycling the now colder air out. I will be testing the effectiveness of this cooling in an insulated larger area than a standard thermoelectric minifridge 17”x17”x17” using styrofoam by collecting data of the heat inside the area and the actual cooling system over time, starting at 90 degrees Fahrenheit (32 degrees celsius) with the system running.

For the technical explanation of how the system works, the system cools the area down in two ways. One is through the absorption of heat from the phase change of ice to water. Two is from airflow blowing over the ice out to the room. This system differs from DIY ice coolers as it doesn't fully rely on blowing air over ice. The system emphasizes the continuous phase change of ice to water as the main cooling method, which would theoretically cool down the area faster. To cool the now melted water back into ice, the fans directing air toward the system stop, and the peltier cooler at the bottom of the tray is turned on, freezing the water over time back to ice. When the water is frozen again the peltier cooler turns off and the airflow toward the ice is turned on again cycling back and forth. To have the peltier cooler run optimally, the peltier cooler must have a slight but not too big temperature difference on each side. A water cooling system on the bottom of the peltier cooler will redirect the hot temperature transferred from the water tray to the outside of the area. A theoretical calculation predicts it taking about 20.3 minutes for 17.6in^3 of water to freeze with a high power peltier module TEC1-12715 assuming optimal conditions at a starting water temperature of 90 degrees fahrenheit.

Water tray volume = 7in*5in*.5in

Water tray volume = 17.6in^3

17.6in^3 ≈ 0.2816 kg

$Q=m \cdot c \cdot \Delta T+m \cdot Lf$

Heat to be cooled in Joules = Mass of water * Specific heat of water * Temperature difference + Mass of water * Latent heat fusion of water (To change back water into ice).

Q = .2816kg * 4184 J/kg * 32C + .2816kg * 334000 J/kg

Q ≈ 1.32 * 10^5J

Assuming cooling down water from 32 degrees Celsius (90 degrees Fahrenheit) to ice.

TEC1-12715 Datasheet Specifies

At 15V*15A=(225W) there is a maximum cooling power of 136W

136/225 ≈ 60% COP (cooling efficiency)

Running the cooler at 12V 15A = 180W

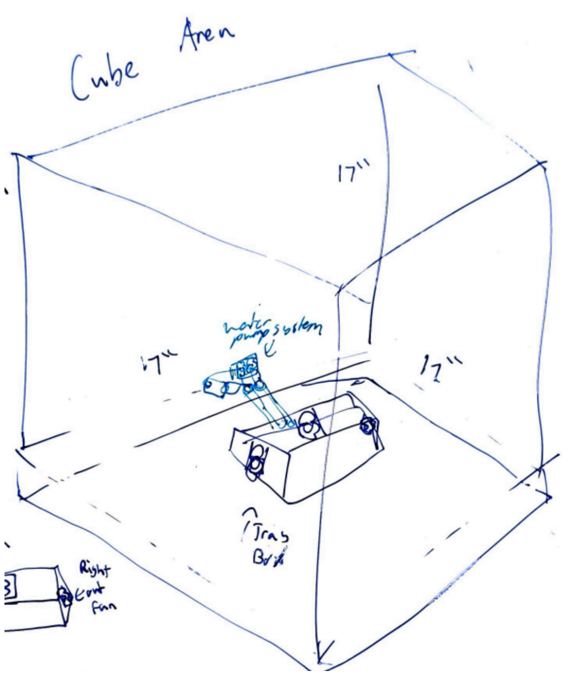
180*.6 = 108W of cooling power

1.32*10^5J/108W ≈ 1220 seconds

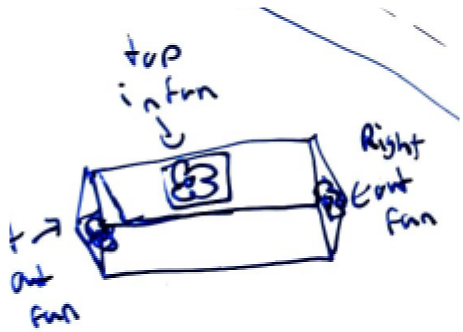
1220sec/60sec ≈ 20.3 minutes to cool ice into water with current setup.

The cooling time should get lower as the room temperature decreases.

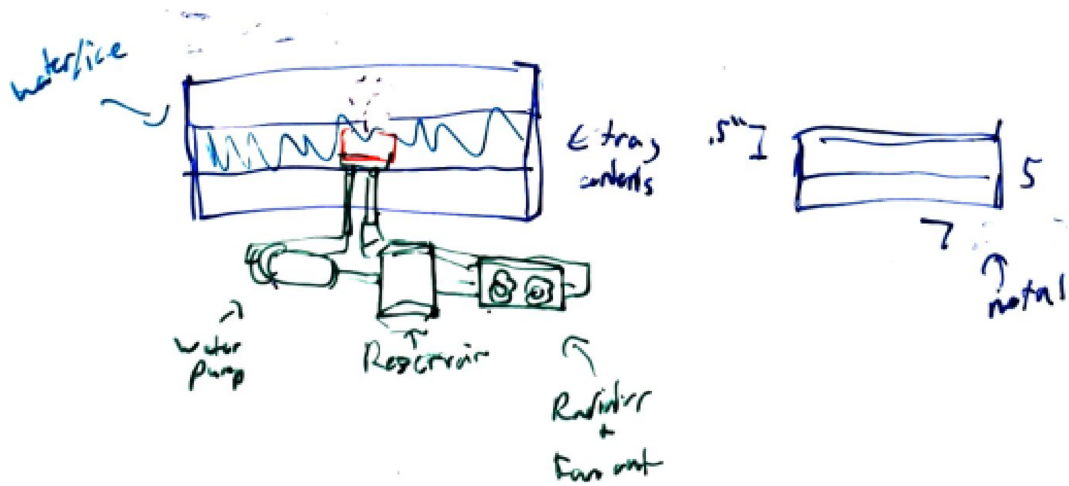
As for the system drawings:



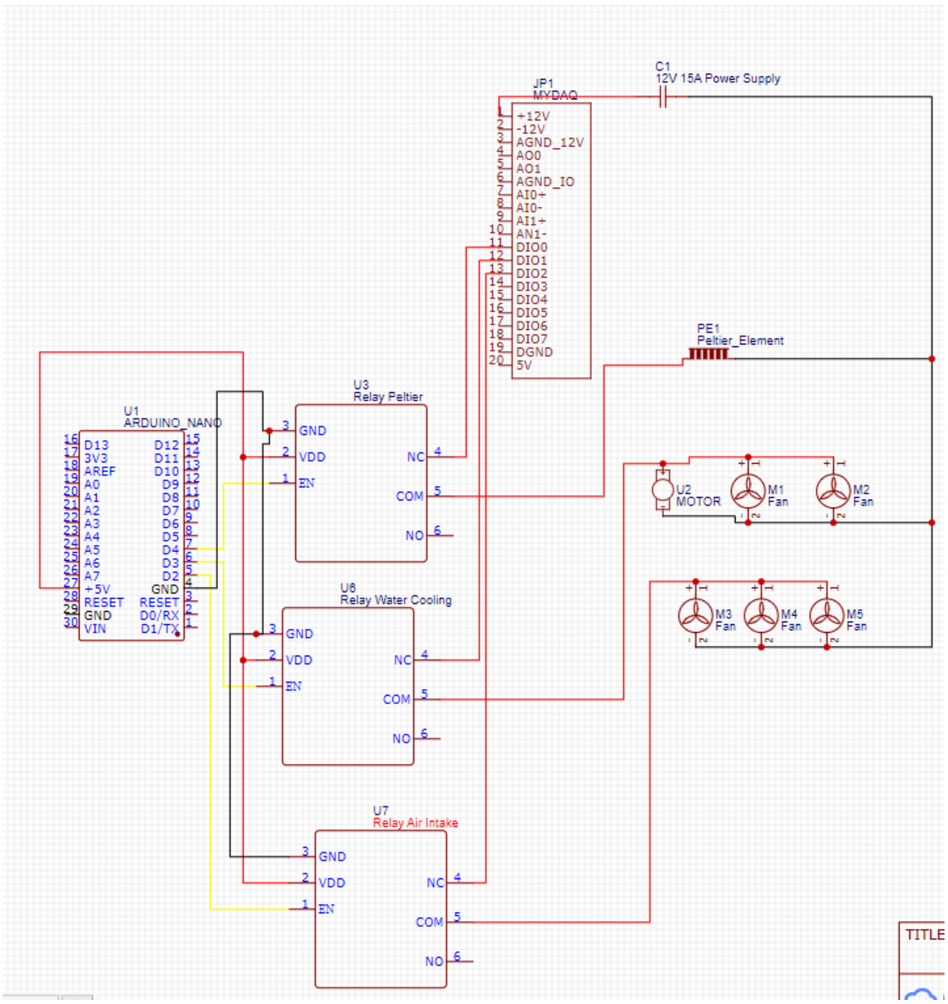
I will be testing in a 17x17x17 inch styrofoam cube (for insulation). The cooling system will go at the bottom middle of the system with water cooling pipes going to the outside.



The cooling system on the outside will have a fan pulling air from on top and distributing air from inside out on the left and right sides.



Inside the cooling system will consist of a metal aluminum tray (high conductivity of temperatures), and will be cooled by a peltier module on the bottom (the red square). Water cooling pipes will be connected to a radiator touching the peltier module and brought through pipes to outside the area where it is cooled. The water cooling system has a water pump for circulation, a reservoir of water to pull from, and a radiator with fans to distribute the heat from the water outside. The water cooling system will keep the peltier module temperature difference low.



This is the schematic diagram for the cooling system. An arduino nano is controlling which parts of the system get power. It will read temperature sensors from within the cooling system and the area around to switch from peltier cooler and water cooling to air flow intake.

As for practicalities, all of the calculations here were done using heat formulas, making them mostly theoretical since outside factors such as temperature leakage can occur. This design is currently not made for mini-fridge like freezing applications, it is meant to cool larger areas drawing less power than modern thermoelectric systems aimed at lowering high temperatures within an area from 90 degrees to 65-70 degrees as the ice will absorb heat slowly in lower temperatures. This system would also not be preferable in more humid areas since one of the methods of cooling the design relies on is airflow over ice which would increase the humidity more making the room as a whole trap more heat. There was also no formula that I could find which can model how much the temperature in a room will decrease when ice is melted because of the widely varying variables impacting the model such as how much airflow from the area gets passed over the ice, how well the inside of the area is insulated, etc…

Risk and Safety

Safety risks deal with the handling of electricity and hot temperatures because of AC to a high watt power supply, however I will take safety precautions such as using heat shrink over exposed cut wire and the proper amp fuses for each component to prevent components from burning out in the case of overdrawing power. The 12V 20A power supply covers all of the components (15A for Peltier Module + 2A for water pump + 1.5A max for fans = 18.5A). All of the components operate at 12V. There is also a low power smart system (the arduino nano) which controls the distribution of power to each component through relays which can always be unplugged fast to turn off the whole system. The water cooling system uses Thermaltake T1000 formula in a contained pipe system, non-conductive in case of spill, meaning it won't damage any components unless left open building up minerals.

Implications

If this design is feasible to cool larger areas at the current electricity usage, more designs and improvements could be made to develop a refined more eco-friendly Air Conditioning unit than the modern air conditioners which use the toxic liquid coolant. Theoretically the design should lower temperatures in an area from 90 degrees fahrenheit to temperatures such as 65-70 degrees fahrenheit with varying running wattage from 240W when cooling to 18W in the passive airflow state. In further research many of smaller conditions can be improved such as better insulation for rooms, better airflow over the PCM, better PCMs to use for this system, and its actual applicableness in modern homes. The research on this design is mainly to test if the concept of a phase change cooling system with thermoelectric cooling would be practical.

Data Analysis

The different data points in cooling systems come down to mainly temperature change over time (rate of cooling), and temperature change compared to electricity usage COP (Coefficient of Performance). The temperature inside the cooling system and in the room will be monitored through temperature sensors hooked up to an Arduino Nano IOT. The Arduino Nano will also keep track of the time the thermoelectric system stays on, and the time the airflow passive state stays on as it controls the power switch to both these systems (through relays) to measure the estimated electricity usage. This data will be sent over the microcontroller's wifi chip through an API, Application Programming Interface which is a data push/request transfer system, to Adafruit IO, a free cloud service which can plot data grabbed by microcontrollers.

Timeline and Budget

There are four main stages of the project: building the styrofoam insulation, coding the smart system to collect data, building the cooling system box, and running and analyzing the data.

Building Outside:

Styrofoam 2x ASIN : B07C969WR8

Nuts and Washers ASIN : B0CLM8HY63

Smart System:

Arduino Nano ASIN: B07WPFQZQ1

Temperature and Humidity Sensor Module ASIN: B09KGW1G41

Waterproof Digital Temperature Sensor ASIN: B08V93CTM2

2 Pcs Relay Module ASIN : B0C4NK5HC4

Cooling System

Power Supply 12V 20A ASIN: B07KRZGKY2

Power Cord to Power Supply ASIN: B07CWS4BGC

20A Terminal Block ASIN: B091F9Y399

14 AWG Wire (Peliter Cooler) ASIN : B017TFR6SM

Alinan 3pcs TEC1-12715 ASIN : B09M7V53CW

18 AWG Wire (Water Pump) ASIN : B0CKQX24QR

20 AWG Wire (Fans) ASIN: B0B9JCXN9M

Aluminum Sheet: ASIN: B08YFJ1JV4

1A Fast Act Fuse ASIN: B01H9XALY0

2A Fast Act Fuse ASIN : B08MYFLTZP

15A Fuse ASIN : B0CS3T4S9L

Water Cooling Radiator ASIN : B0D3LPTT3C

Clear Tubing ASIN : B07NQSNBTG

2A Water Pump ASIN: B0BGY8JS5L

Aluminum Water Cooling Block ASIN: B078MK5GG9

Thermal Paste ASIN: B0795DP124

Acrylic Water Tank Cooler ASIN: B07TVPV3FZ

New Formula Blue Transparent Water Cooling Solution ASIN: B07NRQ8HG8

DARKROCK 3-Pack 120mm Black Computer Case Fans ASIN: B0CD7P3S8Q

Building process explained in Procedures.

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