Project Notes:

Project Title: Enhancing Computer Heat Sink Design with Phase Change Thermal Energy Storage and Thermoelectric Generators
Name: Daniel Kaminski

Contents:

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
How do planes fly using the principles of aerodynamics?	Reading an article about how planes fly.	https://aerocorner.com/blog/how-airplanes-fly/	8/28/21
What types of heat storage exist?	**Researching on what types of thermal energy storage exist.**	**https://www.energytechreview.com/news/3-types-of-thermal-storage-system--nwid-567.html** Citation: Energy Tech Review. (2021, September 3). *3 types of thermal storage system*. Energy Tech Review. Retrieved October 25, 2021, from https://www.energytechreview.com/news/3-types-of-thermal-storage-system--nwid-567.html.	**9/6/21**
What types of silicon chips have existed and what does the history of computer chips involve?	Found an informal article about the history of computing and a little bit of information about computing.	https://www.techwalla.com/articles/how-does-a-printed-circuit-board-work	9/12/21
How Do Peltier's Work?	Found an informal article about the short history, uses, and the mechanics of a Peltier	https://www.reference.com/science/peltier-effect-work-1c6f502da5fb8932	9/18/21
What common	Found a website that	https://www.newegg.c	9/26/21

commercial heatsinks exist for personal use?	sells heatsinks and cooling systems.	om/p/pl?d=cpu+coolers	
What good free CAD software exists?	Found an opinion post about the best free CAD softwares.	https://www.trustradius.com/buyer-blog/top-5-free-cad-software	9/26/21
What PCM's would work well for this project?	Found an article detailing the different types of PCM's that work well at around 50 degrees Celsius.	https://www.1-act.com/products/pcm-heat-sinks/pcmselection/	10/3/21

Literature Search Parameters:

These searches were performed between (Start Date of reading) and XX/XX/2019.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
Google Scholar	Thermal Energy Storage	Found article: *Review on thermal energy storage with phase change materials and applications*
PubMed	Energy Storage, Thermal Energy	Found article: *Nanomaterials in the advancement of hydrogen energy storage*
WPI Library	Sensible Heat	Found Article: *Performance tests on lab–scale sensible heat storage prototypes*
Google Scholar	Immune Boosting	Found Article: *Vitamin D and the Anti-viral State*
Google Scholar	Thermal Energy Storage, Bond Energy	Found Article: *Hydration of Magnesium Carbonate in a Thermal Energy Storage Process and Its Heating Application Design*
WPI Library	Computer Cooling	Found Article: *Review of cooling technologies for computer products*
WPI Library	Wing-span	*Found Article: Stability Characteristics of Wing Span and Sweep Morphing for Small Unmanned Air Vehicle: A Mathematical Analysis*
Free Patents Online	Phase-change material heatsink	Found Patent: *Heatsink for Electrical Circuitry.*
WPI Library	Peltier computer cooler	Found Article: *Modeling and*

		Experimentation of New Thermoelectric Cooler–Thermoelectric Generator Module
WPI Library	Phase change material heatsink	Found Article: *Flexible heatsink based on a phase-change material for a wearable thermoelectric generator*
WPI Library	Phase change material cooling	Found Article: *Experimental study of the cooling performance of phase change material with discrete heat sources – Continuous and intermittent regimes.*
Found as reference in article: *Experimental study of the cooling performance of phase change material with discrete heat sources – Continuous and intermittent regimes.*	NA	Found Article: *Cooling of mobile electronic devices using phase change materials*
Free Patents Online	Phase Change cooling	Found Patent: *Phase-change cooling system*
WPI library/Elsevier ScienceDirect Journals Complete	Thermo-electric generator review	Found Article: *Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials.*
WPI library/Elsevier ScienceDirect Journals Complete	Heatsink Shape	Found Article: *Energy saving potential of using heat pipes for CPU cooling*
Reference in #17	NA	Found Article:*Flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU heat radiator*
WPI library	Thermal paste/grease review	Found Article: *A review of the performance and characterization of*

		conventional and promising thermal interface materials for electronic package applications.
WPI library	Paraffin wax	Found article: *Paraffin wax–water nanoemulsion: A superior thermal energy storage medium providing higher rate of thermal energy storage per unit heat exchanger volume than water and paraffin wax*
WPI library	undervolting CPU thermal	Found article: *Optimizing performance per watt on GPUs in High Performance Computing: temperature, frequency and voltage effects*
WPI library	computer cooling with electricity	Found article: *Performance optimization of cascaded and non-cascaded thermoelectric devices for cooling computer chips*
WPI library	heat recuperation “computer”	Found article: *Development of micro-thermophotovoltaic power generator with heat recuperation*
WPI library	PCM computer review	Found Article: *A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility*
WPI library	PCM computer cooling	Found Article: *Experimental and numerical studies on performance of PCM-based heat sink with different configurations of internal fins*
WPI library	Stirling Engine generator	Found Article: *Simulation, manufacture and experimental validation of a novel single-acting*

		free-piston Stirling engine electric generator
WPI library	Heat to electricity	Found Article: *Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity Directly and Efficiently*
WPI Library	Electrical Generator	Found Article: *Development of a three-stage looped thermoacoustic electric generator capable of utilizing heat source below 120°C*
WPI Library	Simple Stirling Engine Generator	Found Article: *Development of a compact simple unpressurized Watt-level low-temperature-differential Stirling engine*

Article notes should be on separate sheets

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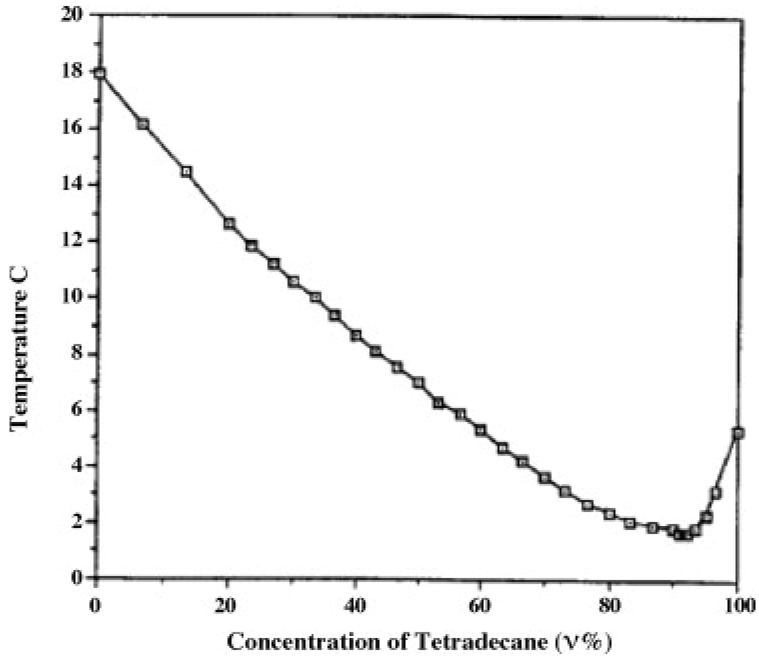
Source Title	
Source citation (APA Format)	
Original URL	
Source type	
Keywords	
Summary of key points (include methodology)	
Research Question/Problem/ Need	
Important Figures	
Notes	
Cited references to follow up on	
Follow up Questions	

Article #1: Review on thermal energy storage with phase change materials and applications

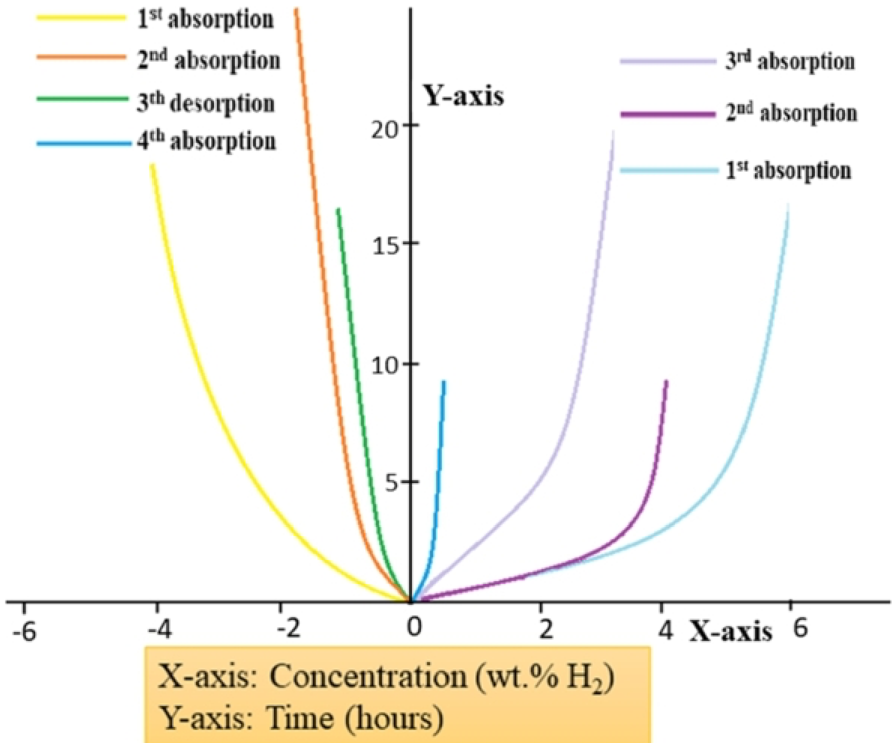
Source Title	*Review on thermal energy storage with phase change materials and applications*
Source citation (APA Format)	Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews*, *13*(2), 318–345. https://doi.org/10.1016/j.rser.2007.10.005.
Original URL	Where it was found (Article can be accessed through website as a PDF):https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S1364032107001402
Source type	Review Article
Keywords	1. Thermal Energy Storage: A system that stores excess heat for later use 2. Phase Change Material: A material that melts under high temperatures in order to store heat 3. Latent Heat: The energy absorbed during the phase change of a substance
Summary of key points (include methodology)	Phase change materials (PCM's) are useful in storing thermal energy because they have a relatively high energy density while being able to maintain constant temperatures. They are also able to store thermal energy without any other inputs for a long time. As these PCM's have varying melting temperatures they can be useful for a wide variety of applications. In the past these have included aerospace thermal control, heat pump, and solar applications (no methodology as this is a review article).
Research Question/Problem/ Need	Are phase change materials (PCMs) a viable method of energy storage?

Important Figures	 This figure shows some information as to how the melting point of PCM's can change depending on the concentration of it's components
Notes	• Phase change materials are materials that can be used to store energy when they melt or solidify, aka. change phases • Thermal energy can be stored by phase change materials • These materials have a variety of melting points, and as such a variety of energy densities usually measured in kJ/kg, or some similar unit. • PCM's can store heat for a long time without leaking any of their energy if they are "trapped" in their state of matter until they are acted upon like with an electrical impulse or with the addition of an impurity. • PCM's and their ability to heat and cool large areas or even small areas has been tested for the past 10 years.
Cited references to follow up on	1. H.P. Garg, S.C. Mullick, A.K. Bhargava Solar thermal energy storage 2. Reidel Publishing Co (1985) Google Scholar 3. Project Report. Energy conservation through thermal energy storage. An AICTE project. Google Scholar 4. N.V. Khartchenko Advanced energy systems Institute of Energy Engineering & Technology University, Berlin (1997) Google Scholar 5. Baylin F. Low temperature thermal energy storage: a state of the art survey. Report no. SERI/RR/-54-164. Golden,

	Colorado, USA: Solar Energy Research Institute; 1979. Google Scholar 6. G.A. Lane Solar heat storage—latent heat materials, vol. I, CRC Press, Inc., Boca Raton, FL (1983)
Follow up Questions	1. Can anything other than PCM's store thermal energy? 2. Is there a limit to the energy density of PCM's that makes them impractical? 3. Do PCM's lose or leak energy over time?

Article #2: Nanomaterials in the advancement of hydrogen energy storage

Source Title	*Nanomaterials in the advancement of hydrogen energy storage*
Source citation (APA Format)	Singh, R., Altaee, A., & Gautam, S. (2020). Nanomaterials in the advancement of hydrogen energy storage. *Heliyon*, *6*(7). https://doi.org/10.1016/j.heliyon.2020.e04487
Original URL	On Pubmed: https://pubmed.ncbi.nlm.nih.gov/32743097/ On Original Site: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7385460/
Source type	Journal Article
Keywords	Chemical Energy Storage, Hydrogen, Energy Density, Hydrogen Storage, Nanomaterial
Summary of key points (include methodology)	Hydrogen can be the key to energy storage in the future. For hydrogen to be useful it must be easy to produce, transport, store, and use. Oftentimes, the methods of hydrogen storage become the limiting factor. Recently, methods of solid-state storage of hydrogen have become available. In this article the methodology tests trapping the hydrogen or bonding it with another material to make it easier to store and to increase its storage density. Already known data was listed and new tests were conducted in order to test the hydrogen storage capabilities of the different substances.
Research Question/Problem/ Need	How do new advancements in hydrogen storage affect its usability?

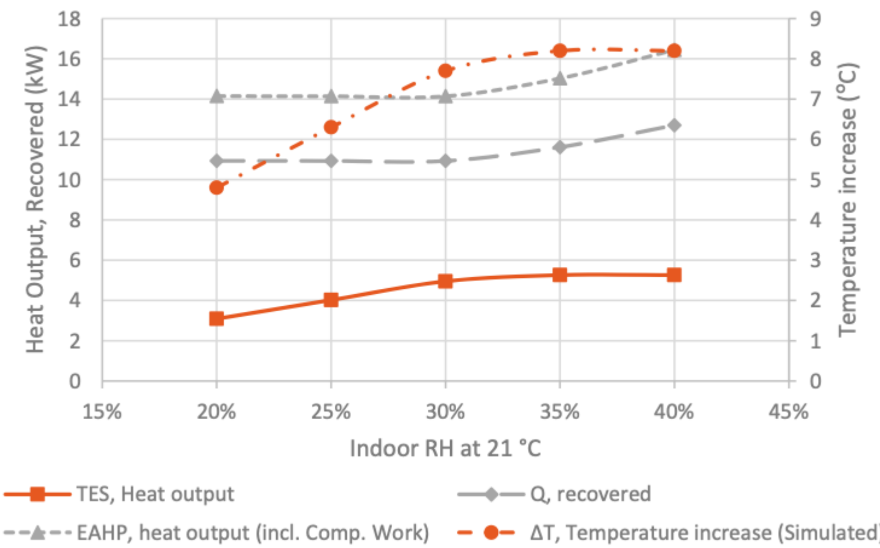
Important Figures	 - This article shows the information about the absorption of hydrogen into the metal organic framework
Notes	● Hydrogen can be used to store energy ● Hydrogen can be stored in its liquid state at high pressures or low temperatures ● Hydrogen can be combusted in order to produce heat ● Many materials can store hydrogen or hydrogen atoms in their molecular structure, such as water, H_2O ● Hydrogen has a gravimetric energy density of 20KJ/g which is three times the energy density of gasoline. ● One of the methods proposed for storing hydrogen is the use of a high pressure tank of 350-700 bars. ● Another method is liquifying hydrogen at temperatures of under 20 degrees celsius. ● Hydrogen can also be absorbed by solid metals as it is a very small atom. However this requires very high temperatures to separate hydrogen from the material it is absorbed into. ● Porous materials can also be combined with metallic materials to store hydrogen.
Cited references to follow up on	1. Eberle U., Felderhoff M., Schueth F. Chemical and physical solutions for hydrogen storage. Angew. Chem., Int. Ed. 2009;48:6608–6630. - PubMed 2. Schlapbach L., Züttel A. World Scientific; 2011.

	Hydrogen-Storage Materials for Mobile Applications. 3. Rowsell J.L., Yaghi O.M. Strategies for hydrogen storage in metal–organic frameworks. Angew. Chem., Int. Ed. 2005;44:4670–4679. - PubMed 4. Yang J., Sudik A., Wolverton C., Siegel D.J. High capacity hydrogen storage materials: attributes for automotive applications and techniques for materials discovery. Chem. Soc. Rev. 2010;39:656–675. - PubMed 5. Panella B., Hirscher M., Roth S. Hydrogen adsorption in different carbon nanostructures. Carbon. 2005;43:2209–2214.
Follow up Questions	1. Is there a limit to how densely hydrogen can be stored? 2. Is hydrogen still volatile with these storage methods? 3. Does storing it in these ways make it heavier to store the same amount of hydrogen, thus making it less efficient to transport?

Article #3: Hydration of Magnesium Carbonate in a Thermal Energy Storage Process and Its Heating Application Design

Source Title	**Hydration of Magnesium Carbonate in a Thermal Energy Storage Process and Its Heating Application Design**
Source citation (APA Format)	Erlund, R., & Zevenhoven, R. (2018). Hydration of magnesium carbonate in a thermal energy storage process and its HEATING application design. *Energies*, *11*(1), 170. https://doi.org/10.3390/en11010170.
Original URL	https://res.mdpi.com/energies/energies-11-00170/article_deploy/energies-11-00170.pdf
Source type	Journal Article
Keywords	1. Adsorption: The accumulation of some substance on the surface on another substance 2. Geothermal: Relating to the internal heat of the Earth 3. Sorption: The process of being absorbed or adsorbed 4. Zeolite: Any hydrated double silicate in which the main bases are calcium, sodium, and aluminum. 5. Porosity: The quality of being porous. 6. Hydration: The chemical combination of water molecules or groups with a substance.
Summary of key points (include methodology)	The main goal of this experiment was to determine how to hydrate thermal energy storing chemicals in order to achieve the optimum thermal output. The chemicals used to store the thermal energy are chemicals that become “dehydrated” when exposed to a high temperature and when “hydrated” release that thermal energy. Thus the goal was to best hydrate the chemicals. The substances used are nesquehonite which is a clear mineral with a high energy storage density and silica gel, which has a lower energy density but a lower dehydration temperature as well. When combined a relatively high thermal energy density was maintained while the dehydration temperature was significantly lowered. The hydration was then tested as different atmospheric humidity. It was found that the energy density at 40% humidity was 0.32MJ/kg while at 75% it was 0.68 MJ/kg. From this the conclusion was drawn that the higher the higher atmospheric humidity during rehydration of chemicals result in higher

<table>
<tr><td></td><td>energy yields. Thus, an important step was made in realizing a more efficient hydration process for better optimization of thermal energy storage.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>What is the ideal way to hydrate a chemical in order to store thermal energy?</td></tr>
<tr><td>Important Figures</td><td>



This figure demonstrates the heat output of different systems and the temperature differences that result from it.</td></tr>
<tr><td>Notes</td><td>

- Heat in this system would be stored by “dehydrating” a substance and it would be released by “hydrating” a substance.
- Hydration in this case means chemically combining a substance with water and dehydration means chemically separating the substance from water.
- This article focuses on improving the “hydration” or heat release section of thermal energy storage.
- The thermal energy storage material in this article was a mix of nesquehonite (a clear crystalline mineral) and silica gel.
- Nesquehonite and silica gel have chemical formulas $MgCO_3 \cdot 3H_2O$ & SiO2 • H2O respectively.
- The chemicals can be hydrated using either water vapor generated using geothermal heat or simply using atmospheric humidity.
- The energy yield is more than twice higher when hydrated at a 75% relative humidity as opposed to a 40% relative humidity.

</td></tr>
<tr><td>Cited references to</td><td>1. Edem N’Tsoukpoe, K.; Liu, H.; Le Pierrès, N.; Luo, L. A</td></tr>
</table>

follow up on	review on long-term sorption solar energy storage. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2385–2396. [CrossRef] 2. Bauer, D.; Marx, R.; Nußbicker-Lux, J.; Ochs, F.; Heidemann, W.; Müller-Steinhagen, H. German central solar heating plants with seasonal heat storage. *Sol. Energy* **2010**, *84*, 612–623. [CrossRef] 3. Whiting, G.; Grondin, D.M.; Bennici, S.; Auroux, A. Heats of water sorption studies on zeolite–MgSO4 composites as potential thermochemical heat storage materials. *Sol. Energy Mater. Sol. Cells* **2013**, *112*, 112–119. [CrossRef]
Follow up Questions	1. How could dehydration be improved as well as that is where the thermal energy enters the system? 2. What design of a reactor could best capture thermal energy during the summer in order and dehydrate the thermal energy storing substances? 3. What materials reflect the least amount of thermal and light energy? 4. Could the water that was chemically removed from the mixture during dehydration be recycled for hydration? 5. How expensive would a system with a water vaporizer and multiple reactors be when compared to traditional renewable energy sources such as solar and wind.

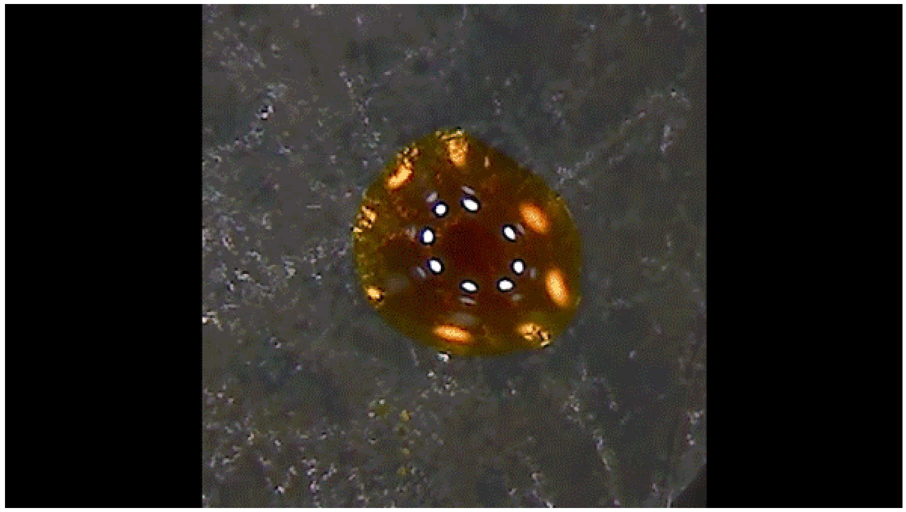
Article #4 Notes: Vitamin D and the Anti-Viral State

Source Title	**Vitamin D and the Anti-viral State**
Source citation (APA Format)	Beard, J. A., Bearden, A., & Striker, R. (2011). Vitamin d and the anti-viral state. *Journal of Clinical Virology*, *50*(3), 194–200. https://doi.org/10.1016/j.jcv.2010.12.006
Original URL	https://www.sciencedirect.com/science/article/pii/S1386653210004932?casa_token=tMUSYv8NoaMAAAAA:jP0a-kL2ibVCtckOuAa25qb95VO1zqYo-ECIR7G91eCTm8gbOBzXNC7KlW2d2UoNVmzQ0URJ
Source type	Review Article
Keywords	1. Anti-viral: Acting against viruses 2. Vitamin D: A vitamin necessary for bone structures that is chemically similar to steroids and is present in many animal products 3. Vitamin: A non energy giving substance needed in small quantities for the continuation of homeostasis and regular body functions in a living organism that acts as an enzyme or coenzyme for metabolism. 4. Peptide: A group of two amino acids connected by one's amino group with the other's carboxyl group. 5. Homeostasis: The process of an organism achieving stability between elements of itself through equilibrium of these elements.
Summary of key points (include methodology)	In this review article the ability of Vitamin D to regulate and improve immune responses is discussed. Aside from these uses, vitamin D is also a vital part of the skeletal systems It is hypothesized that the way that Vitamin D affects the immune system is through activation of T cells (white blood cells) and through activating certain other immune genes. As this is a review article, no methodology was discussed and other article's methodology was discussed instead. The results indicate that Vitamin D does in fact have significant immune boosting capabilities as it can induce the production of the LL-37 peptide which is an antimicrobial peptide which has been found to significantly affect viruses as well. However, this in of itself was not found to be enough to fully evaluate the effect of Vitamin D on the immune system and the immune systems' antiviral capabilities so further experimentation is needed.
Research Question/Problem/	How does vitamin D affect the body and how does it affect viral infections in the body?

Need	
Important Figures	
Notes	● Vitamin D is an essential part of the skeletal system ● Vitamin D is also seen to play a major part in the operation of the immune system ● The evidence for vitamin D's effect on the immune system is so far experimental and not theoretical, although it is believed that vitamin D can regulate peptides and other chemicals in the body that act as anti-pathogens and antimicrobial agents. ● It is also found that people with HIV often have vitamin D deficiency. ● Vitamin D is extremely effective against enveloped viruses (viruses enveloped with a lipid membrane) ● Ongoing tests on Vitamin D test its ability to help against viral, bacterial, cardiovascular, and cancer related health issues.
Cited references to follow up on	1. D.D. Bikle Vitamin D and immune function: understanding common pathways Curr Osteoporos Rep, 7 (2009), pp. 58-63 2. J. Miller, R.L. Gallo Vitamin D and innate immunity Dermatol Ther, 23 (2010), pp. 13-22 3. C.F. Garland, E.D. Gorham, S.B. Morh, F.C. Garland Vitamin D for cancer prevention: a global perspective Ann Epidemiol, 19 (7) (2009), pp. 468-483
Follow up Questions	1. How is vitamin D produced in animals and in the body? 2. Is vitamin D that is commonly sold produced naturally and extracted or is it chemically synthesized? 3. What adverse effects does too much vitamin D have on the body? 4. Do people of a certain age group benefit from supplements such as vitamin D more than others?

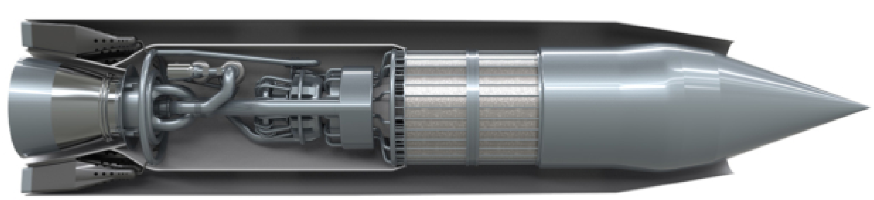
General Article #1: A new way to store thermal energy.

Source Title	A new way to store thermal energy
Source citation (APA Format)	Chandler, D. L. (2017, November 16). *A new way to store thermal energy*. MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2017/new-way-store-thermal-energy-1117.
Original URL	https://news.mit.edu/2017/new-way-store-thermal-energy-1117
Source type	Website Article
Keywords	1. State of matter: A description for the physical characteristics of matter dependent on the kinetic energy of the particles 2. Chemical bond: Either an ionic, covalent, or metallic bond where atoms are bound to each other or to a material. 3. Phase change material: 4. Solar energy: Energy that reaches the earth from the sun, and can be transmitted through light, radiation, or heat.
Summary of key points (include methodology)	At MIT a material was developed that could store solar thermal energy that is abundant during the day and release it during the night. It does this by turning from a solid state to a liquid state. However, this phase change material (PCM) does not release energy uncontrollably, but has molecular switches that keep it as a liquid until shone at with light, which then can uncontrollably release the heat energy from the material. The methodology included lipids phase change materials and combining them with an organic compound that reacts to light, which controls the phase change. This combined PCM can hold the thermal energy for up to 10 hours and can cause a temperature change of up to 18 degrees Fahrenheit. So this material offers an alternative method of solar energy storage. This is useful for my project because it offers an alternative method of energy storage. Rather than storing energy in chemical bonds and then breaking them to release energy, this shows that it is also possible to use phase changes to store and release thermal energy. So this provides a further avenue for experimentation and previous experimental knowledge.
Research	How can thermal energy better be stored and released when

Question/Problem/ Need	needed?
Important Figures	This is an image of the melting pcm 
Notes	● A material was made at MIT to store thermal energy and release it consistently. ● In order to store this energy a phase change material was used, or a PCM that melts when it has access to energy and then releases it later. ● In order to prevent the PCM from solidifying the substance was mixed with “molecular switches” that can trigger it’s phase change ● The substance used was a mixture of fatty acids that have a relatively low melting point and an organic material that is light sensitive. When light is shone at the light sensitive material, it triggers the phase change of the fatty acid. ● The temperature change that can be achieved is currently 10 degrees Celsius. ● The material can maintain it’s phase for up to 10 hours. ● The energy density of the material is high at 200 joules/gram.
Cited references to follow up on	NA
Follow up Questions	1. Are PCM’s cheap to make or are they more expensive than traditional energy sources? 2. Are the organic materials used as molecular switches easy to make as well? 3. Can these materials be mass produced? 4. How can these be implemented into everyday appliances? 5. What is the upper limit of storage time for this material?

General Article #2: Air Breathing Rocket Engines: The Future of Space Flight

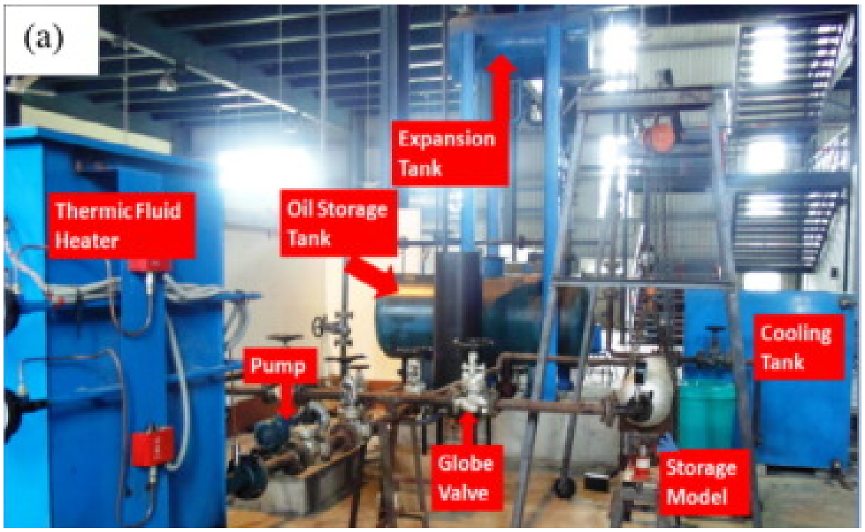
Source Title	Air-breathing rocket engines: The future of space flight
Source citation (APA Format)	Physics World. (2020, October 15). *Air-breathing rocket engines: The Future of Space Flight*. Physics World. https://physicsworld.com/a/air-breathing-rocket-engines-the-future-of-space-flight/.
Original URL	https://physicsworld.com/a/air-breathing-rocket-engines-the-future-of-space-flight/
Source type	Website Article
Keywords	1. Rocket engine: An engine used for the propulsion of a spacefaring vehicle 2. Oxidation: Either when a substance gives away valence electrons, or when a substance combines with oxygen 3. Mach: The name for the speed of sound, or 767mph 4. Combustion: The usually heat producing redox process in which a fuel and an oxidant combine to produce a certain gaseous substance. 5. Thermal energy transfer: The process of atoms in one substance moving thermal energy from themselves to the atoms of another substance
Summary of key points (include methodology)	This article discusses the invention and design of the new SABRE rocket engine. It discusses by first describing the benefits of space travel. From GPS, global relief and observation and the internet, the benefits of space travel are innumerable. While there have been big breakthroughs by private companies in the past few years, the accessibility and practicality of traditional space flight is limited by the abilities of the engines that fuel it. As most conventional engines use a mixture of some combustible fuel and oxygen, the SABRE engine instead gets its oxygen during the atmospheric ascent from the air around it and will only switch to onboard oxygen after leaving the atmosphere. This means that the weight of the fuel needed will be reduced, thus allowing for higher weight payloads and more powerful engines. The aircraft that will utilize the engine will also launch horizontally like a plane, which provides many benefits such as safer

	aborts and turnarounds and simpler launch requirements. The way that the SABRE (Synergetic Air Breathing Rocket Engine) works is by using the air that is coming into the engine and slowing it down so that it can be used for combustion. However, this is not possible in traditional rocket engines because for the air to be used at speeds such as Mach 5 it must be slowed down, and when it is slowed down it heats up to temperatures of around 1000 degree Celsius which melts the engine. Thus, the SABRE engine uses a pre-cooler, or a very long and thin pipe filled with liquid helium to cool down the oxygen after it has been slowed down by the engine's interior design. This "pre-cooler" was tested at speeds of up to Mach 5, quicker than any vehicle using atmospheric oxygen before, and was able to cool down the air to room temperature in less than 50 milliseconds, the time allotted for the operation of the cooler during real applications. As such the 700 trial runs done are considered to be successful. One of the main benefits of this technology is in hypersonic and motorsport vehicles as the cooling technology is on a new tier of thermal energy transfer rates. In the SABRE engine the thermal energy that is removed will then be used for combustion and other processes within the engine. The SABRE engine and its applications are the perfect example of a fusion between traditional rocketry and traditional aircraft resulting in a more practical approach to space travel. Space travel is something that interests me greatly and learning about the applications of new propulsion methods opens up many new possibilities such as trying to build small scale models of engines like the SABRE or just trying out new cooling or propulsion methods. As such this article provides information about the different types of propulsion methods being developed today.
Research Question/Problem/ Need	How can rocket engines become more efficient by using atmospheric oxygen?
Important Figures	
Notes	● Most engines require a fuel and an oxidant, adn this must

	carry more weight ● Because most engines need both a fuel and an oxidant on traditional rockets both types of substance are carried. ● Hydrogen and oxygen can be used for combustion ● Reducing the weight of the oxidant carried by getting it from the air around the ship allows for more of the fuel, and thus more power and range. ● Such engines as the SABRE add more complexity and thus more points of failure. ● If not enough oxidant is received from the environment the engine could fail. ● Such an engine could increase the possibilities of a combustion engine.
Cited references to follow up on	NA
Follow up Questions	1. What would happen if not enough oxygen was present? 2. Would this engine be more heavy and thus defeat the purpose? 3. Could any type of fuel be used for this engine? 4. For how long would the pre-cooler function optimally? 5. Does the thinness of the pre-cooler pipe cause it to be susceptible to sympathetic vibration and other types of damage during flight?

Article #5: Performance tests on lab-scale sensible heat storage prototypes

Source Title	Performance tests on lab–scale sensible heat storage prototypes
Source citation (APA Format)	Rao, C. R. C., Niyas, H., & Muthukumar, P. (2018). Performance tests on lab–scale sensible heat storage prototypes. *Applied Thermal Engineering*, 129, 953–967. https://doi.org/10.1016/j.applthermaleng.2017.10.085.w
Original URL	https://wpi.primo.exlibrisgroup.com/view/action/uresolver.do?operation=resolveService&package_service_id=3890842310004746&institutionId=4746&customerId=4745
Source type	Journal Article
Keywords	1. Sensible Heat Storage (SHS): A method of storing heat in which the heat is stored by heating up a substance and then allowing it to cool down in order to harvest that heat. 2. Heat exchanger: A system or device used to transfer heat between two liquids or solids. 3. Thermal Diffusivity: How quickly a material can transfer heat from it's hot side to it's cold side. 4. Heat transfer fluid (HTF): A fluid that has a high thermal conductivity rate used in thermal applications to transfer heat 5. Charging Time: The time it takes for the sensible heat storage system to heat up to full capacity. 6. Concrete: A substance consisting of fine and large particles bound together by a cement binder.
Summary of key points (include methodology)	In this article 3 sensible heat storage prototypes were tested, each containing concrete as the thermal energy storage material, synthetic oil as the thermal energy transfer fluid, and a pipe with some metal to be used as fins. The three variations of the fin materials were cast steel, copper, and mild steel (mild as in the carbon percentage). The designs were tested by heating the synthetic oil and running it through pipes with a pump, with the pipes placed into the concrete storage container. Thus the concrete was heated up. The temperatures of the synthetic oil were changed and the charge and discharge rates as well as the thermal energy absorbed by the concrete was tested. The results indicated that the cast steel design had the quickest charge and discharge rates as well as the highest energy density. The next highest results were from copper and the third highest were from the mild steel. As a result the researchers

	found that a sensible heat storage system with concrete as the main storage material, synthetic oil as the heat transfer fluid and cast steel fins performs the best out of the three designs. The final energy density of the system was 15MJ. After 150 charge/discharge cycles no significant degradation in performance was found, indicating that such a design could be implemented into the real world and provide an alternative energy source.
Research Question/Problem/ Need	Which fin metal best allows for an efficient and energy dense sensible thermal energy storage design?
Important Figures	
Notes	● The system is made out of steel and concrete ● The design is a shell-tube design heat exchanger ● The capacity for heat storage is 15MJ ● The performance was improved by adding fins onto the heat transfer fluid tubes, thus increasing heat transfer rates ● The design greatly impacts the charging/discharging rates and the temperature does as well ● According to the authors the main barrier stopping solar thermal energy from becoming a large energy source for the world is the ability of designs to intercept and store thermal energy ● Thermal storage materials are often not long living ● Sensible heat storage has the lowest energy density out of phase change materials and thermo-chemical energy storage buth thermo-chemical energy storage is expensive and complicated and phase change material have a low thermal conductivity rate ● Castable ceramic and concrete are some of the best materials for sensible heat storage

	• To increase the thermal conductivity rate of concrete cast iron could be used and fins could be attached to it • Three designs were used, the first with concrete and cast iron fins, the second with concrete and copper fins and the last with concrete and mild steel fins • The system worked by heating up the thermal fluid and then pumping it around a system thus testing the sensible heat storage system. The heat transfer fluid in this case was oil • There were multiple pipes running through the concrete each with fins for thermal dissipation • Out of the three designs, the one with cast iron fins best dissipated heat and thus had the best heat storage density as well • The M1 or cast iron design also had the quickest charging and discharging rates • After 150 test cycles no significant problems or lower results occurred
Cited references to follow up on	1. D. Laing, T. Bauer, D. Lehmann, C. Bahl, Development of a thermal energy storage system for parabolic trough power plants with direct steam generation, J. Solar Energy Eng.-Transact. ASME 132 (2010). 2. O.E. Ataer, Storage of thermal energy, in: Encyclopedia of Life Support Systems (EOLSS), 2008. 3. A. Mawire, M. McPherson, R.R.J. van den Heetkamp, S.J.P. Mlatho, Simulated performance of storage materials for pebble bed thermal energy storage (TES) systems, Appl. Energy 86 (2009) 1246–1252.
Follow up Questions	1. How much would such a system cost? 2. Where would the thermal transfer fluid be placed in order to best collect heat in the real world? 3. Would another system be needed to transfer heat from the outside of the heat transfer fluid? 4. Would the heat contained in the concrete be sufficient to boil water in a turbine generator? 5. Could this feasibly introduce more uncertainty points and more points of failure than a traditional coal or oil electric plant? 6. Would a nuclear plant have a higher energy density per amount of radioactive material versus the energy per amount of concrete? 7. Could the heat transfer fluid also be changed? Perhaps the speed of it’s flow could be changed at a wider range?

Article #6: Review of cooling technologies for computer products

Source Title	Review of cooling technologies for computer products
Source citation (APA Format)	Chu, R., Simons, R., Ellsworth, M., Schmidt, R., & Cozzolino, V. (2004). Review of cooling technologies for computer products. *IEEE Transactions on Device and Materials Reliability*, 4(4), 568–585. https://doi.org/10.1109/TDMR.2004.840855.
Original URL	https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1388428 Or https://ieeexplore-ieee-org.ezpv7-web-p-u01.wpi.edu/stamp/stamp.jsp?tp=&arnumber=1388428&tag=1
Source type	Review Article
Keywords	1. Flow boiling: When a device is used to force or boil fluid out of a container and over the edge 2. Heat sink: A device used to absorb any unneeded heat in a computer by maintaining contact with a computer chip and drawing heat from it 3. Immersion cooling: When a computer component is directly submerged in a thermally conductive substance and it is circulated in order to draw heat from the components 4. Impingement cooling: When a gas or liquid is moved continuously onto a surface in order to draw heat away from it 5. Computer chip: A silicon processing unit made of micro-transistors used to complete calculations in a computer 6. Heat flux: The amount of heat that can flow in a given area per unit time 7. CPU: the central processing unit of a computer 8. Thermal paste: A usually semi-liquid material used on top of chip silicon to fill in micro-gaps and allow for better thermal conductance
Summary of key points (include methodology)	As this article is a review article no methodology will be included. The goal of this article was to review all of the methods of cooling computers and their efficacy and efficiency. Throughout the years computers have become more and more efficient and more and more powerful, thus consuming more and more electricity and generating more and more heat. All of this heat needs to be dissipated as computers can only operate while they are running at a low temperature, in fact a computer chip running at 100 degrees Celsius is about 2.5x slower than a chip running at around -200

	degrees Celsius. One method of cooling chips is by running air through the chip or over it, and additionally fins can be added to the heatsink in order to maximize cooling potential. A cold plate or water cooling can be used in order to bring the chip into contact with a more thermally conductive and energy dense liquid. A system run by using periodic piston connection and a cold plate can achieve a heat flux of up to $64W/cm^3$. The internal cooling of a computer chip can also be improved in multiple ways. For example, the chip itself can be immersed in a liquid, or can be put in a forced convection area where liquids or gases are blown over the silicon. Also, a supercooled liquid can boil and cool down a plate thus cooling the silicon with a heat flux of up to $30W/cm^3$. A liquid cooling forced convection system can achieve a heat flux of $100W/cm^3$ if it is internal and directly in contact with the chip, however it is important that the liquid is suitable, and fluorocarbons are often used. Additionally, hybrid systems can be used where a coolant is cooled further via another cooling method as it runs through the system. Similarly, refrigerants can be used for this purpose or simply for other cooling methods, and the type of refrigerant can greatly impact the heat flux. All of this is important because the lower the temperature of a computer the more can be done, expecilla in research, database, or commercial applications. This also introduces the challenge of cooling systems for databases and computing centers. Overall, cooling computers is a difficult and important job that can be done via many different processes.
Research Question/Problem/ Need	What methods of computer cooling are the most effective and efficient in real world applications?

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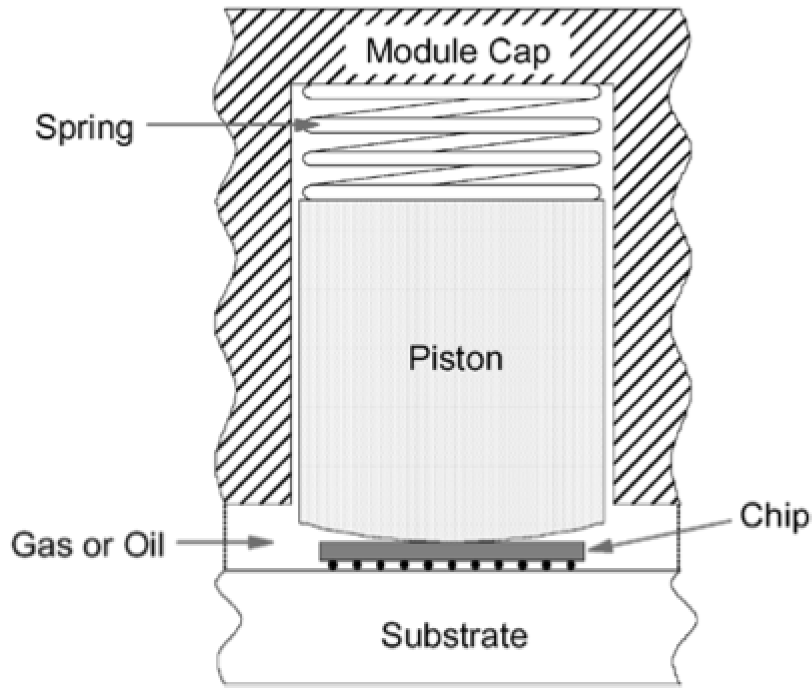
<tr><td>Important Figures</td><td>


This is a design that utilizes gas compression temperature differences

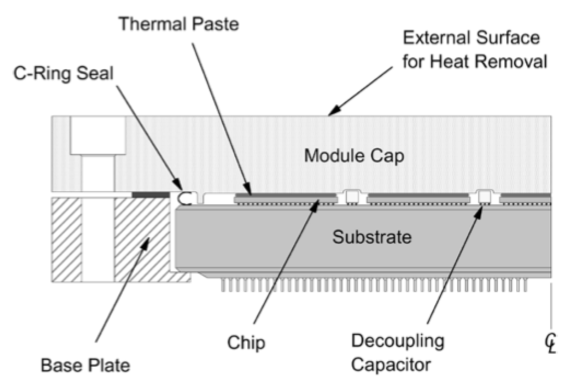


Fig. 6. Cross-sectional view of central processor module package with thermal paste path to module cap [9].

Below is an example of a typical sensible heat storage cooler
</td></tr>
<tr><td>Notes</td><td>

Computers rely on better and better cooling methods in order to facilitate more and more powerful processors
Many times the high temperature output of a cooling system is places right next to the cooling input
A typical and simple heat sink would involve simply putting a thermal paste on top of the CPU (central processing unit) and then layering a finned piece of metal on top for heat dissipation

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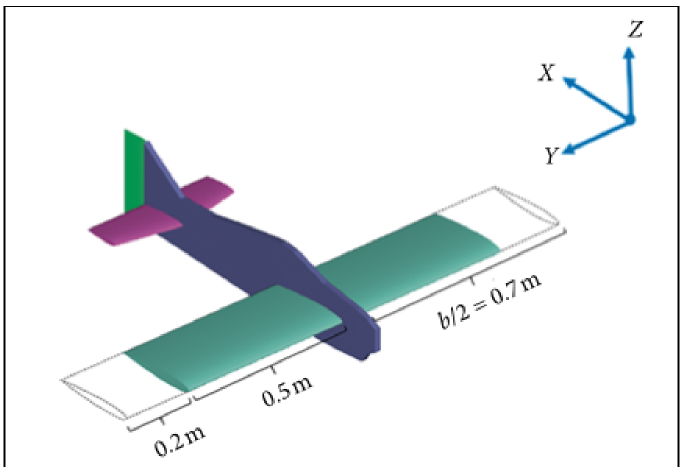
</table>

	● Similarly, by using helium powered pistons that periodically touch chips and a water cooled cold plate a chip can also be cooled with a maximum chip cooling ability of $64w/cm^3$ ● In order for the power of chips to keep increasing cooling/heat flux also has to increase ● There is an internal cooling solution which would be the cooling system inside of the packaged cpu silicon and printed circuit board (PCB), and the external cooling which is the solution outside of the cpu package ● Phase change materials can be used on cpu heatsink cooling fins to reduce thermal resistance between the metal and air ● Thermal paste is used to fill the gaps between two surfaces to better transfer heat ● Microchannels etched into a computer chip connected to a cold plate water cooling method can be very effective for cooling ● Immersion cooling immerses the chip into it's coolant, and the most used liquid is fluorocarbons ● Forced convection of liquids or gasses over chips can also be used to increase cooling performance ● Boiling liquids can also be used to cool a chip as boiling a liquid creates a decrease in temperature, and can have a heat flux of $30W/cm^3$ ● If such a liquid system is used at the internal cooling level a heat flux of $100W/cm^3$ can be achieved ● Hybrid systems can be used when one type of cooling is not enough, ex., the air going through a system heats up and is then cooled via water cooling ● Electronics perform better at lower temperatures, even at almost absolute zero temperatures ● Refrigerant can also be used to cool a heat sink ● Commercial computing centers or supercomputing centers often need to cool their floors and introduce cold air flow systems
Cited references to follow up on	1. A. E. Bergles, "The evolution of cooling technology for electrical, elec- tronic, and microelectronic equipment," ASME HTD, vol. 57, pp. 1–9, 1986. 2. R. C. Chu and R. E. Simons, "Cooling technology for high performance computers: Design applications," in Cooling of Electronic Systems, S. Kakac, H. Yuncu, and K. Hijikata, Eds. Boston, MA: Kluwer, 1994, pp. 97–122. 3. J. R. Culham and Y. S. Muzychka, "Optimization of plate fin heat sinks using entropy generation minimization," IEEE Trans. Compon. Packag. Technol., vol. 24, no. 2, pp. 159–165, Jun. 2001.

	4. M. Gao and Y. Cao, “Flat and U-shaped heat spreaders for high-power electronics,” Heat Transfer Eng., vol. 24, no. 3, pp. 57–65, May/Jun. 2003. 5. F. Roknaldin and R. A. Sahan, “Cooling solution for next generation high-power processor boards in 1U computer servers,” Adv. Electron. Packag., vol. 2, pp. 629–634, 2003
Follow up Questions	1. Can thermo-chemical energy storage methods be used to cool computers? 2. Could sensible heat storage be used to absorb the large amount of computer thermal energy and then be redistributed for something like electrical generation or home heating? 3. Could more computer centers be built in colder areas for easier cooling? 4. Do computers contribute any appreciable amount of energy on a global scale 5. Could data centers be submerged in places like the ocean for better cooling?

Article #7: Stability Characteristics of Wing Span and Sweep Morphing for Small Unmanned Air Vehicle: A Mathematical Analysis

Source Title	Stability Characteristics of Wing Span and Sweep Morphing for Small Unmanned Air Vehicle: A Mathematical Analysis
Source citation (APA Format)	Muhammad Umer, H., Maqsood, A., Riaz, R., & Salamat, S. (2020). Stability Characteristics of Wing Span and Sweep Morphing for Small Unmanned Air Vehicle: A Mathematical Analysis. *Mathematical Problems in Engineering*, 2020, 1–15. https://doi.org/10.1155/2020/4838632
Original URL	https://www.hindawi.com/journals/mpe/2020/4838632/
Source type	Journal Article
Keywords	1. Wing sweep angle: The amount that a wing angles forwards or backwards towards the nose of the plane 2. Wing span: The length of the wings of a plane from their tip of one wing to the tip of another wing 3. Trim point: The point at which a part of the plane that is used to control its movement is moved 4. Wingspan morphing: The process of adjusting the wingspan 5. Unmanned Air Vehicle (UAV): An aircraft without any human pilot or human control input 6. Planform: The way that an airplane's wing is shaped and designed. 7. Attack angle: The angle at which the UAV is flying against the wing in order to reach a target position
Summary of key points (include methodology)	In this article a mathematical analysis of unmanned vehicles with adjustable wing sweep and wingspan was done. This was done in order to determine how unnamed air vehicles (UAVs) can better be improved in terms of aerodynamic stability and aerodynamic ability because the needs of such UAVs is so wide and the missions require many different aerodynamic situations. In order to test the wing sweep and wingspan a Vortex Lattice Method (VLM) was used in order to simulate a small UAV made of polystyrene and carbon-fiber structure rods with adjustable wingspan and wing sweep. The wingspan could be adjusted from 0.5m for each wingo to 0.7m for each wing, while the wing sweep could be adjusted to be up to 30

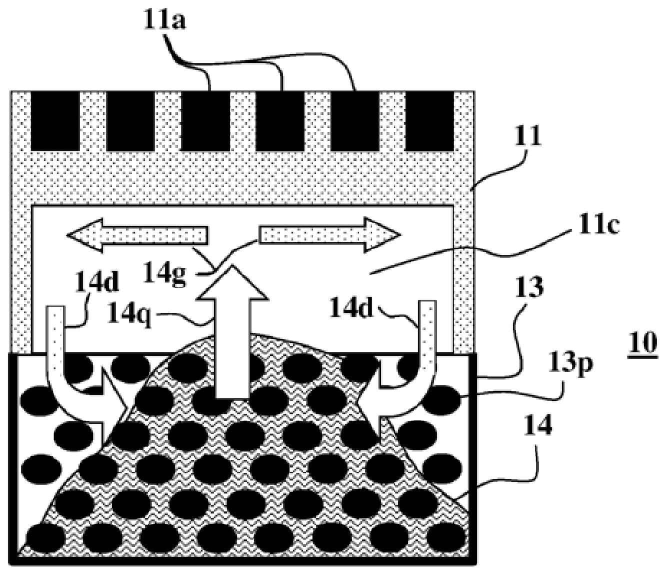
	degrees towards the plane's tail. After this the trim needed in order to maintain aerodynamic stability was tested using the VLM through the testing of multiple directions of stability and attack angles. The results indicate that increasing the wingspan negatively impacts the longitudinal and directional stability of the UAV but increases the lateral stability at high angles of attack. The increase of the wing sweep results in overall increased stability but a lower lack of ability to dive and spring. The results indicate that overall both methods of increasing the aerodynamic stability can contribute to better aerodynamic abilities however the benefit of such a system is that if a certain change creates drawbacks in another area it can be implemented only when the situation calls for it. Overall, the results indicate that the more recommended method of modular UAV trim would be to create modular wingspan.
Research Question/Problem/ Need	How can the aerodynamic stability of Unmanned Air Vehicles (UAV's) be best improved using wingspan and wing sweep morphing?
Important Figures	 (a) ● ● This is the modeled UAV
Notes	● Unmanned Air Vehicles (UAVs) often have trouble meeting the aerodynamic requirements for missions because of the wide range of needs ● This article took inspiration from the idea that bird's change their wing shape in order to test the effect of changing wing-shape on the aerodynamic capabilities of UAVs. ● Wingspan and sweep angle are the main platforms that can be changed in order to affect aerodynamics. Changing these things can result in different lift-to-drag ratios, the inertia of the plane, etc. ● Inflatable telescope wings can be used in order to greatly

	change the wingspan of a plane by up to 114% ● Higher wing sweep can allow a plane to have quicker “dash” speeds but a lower wing sweep can allow for longer endurance and fuel economy. Thus an adjustable wing sweep can make an aircraft suitable for both. ● The calculations for stability and aerodynamics in this article were done with the Vortex Lattice Method (VLM) which is a method for calculating fluid dynamics ● In order for morphing to work there have to be actuators, strong materials, and good load bearing designs ● Smaller UAVs have bigger changes in flight from smaller planform changes ● Many UAVs are controlled by Automatic Flight Control System (AFCS) ● The plane that was geometrically designed to be tested was a basic design with an polystyrene body and carbon fiber rod reinforcement ● This design can sweep wings up to 30 degrees ● It was found that morphing the modeled aircraft affects the stability more than it’s aerodynamic capabilities ● Increasing the wingspan **reduces** stability while increasing the sweep angle **increases** stability ● The higher the angle of attack the more stability efforts need to be made and in this case increasing the wingspan can significantly decrease the need for elevator angle changes. Additionally, the higher the wingspan is the less thrust is needed to maintain a high velocity for attacks because of the increased lift. ● The plane’s longitudinal stability is decreased with increasing wingspan while higher sweep results in higher stability ● Lateral stability increases with higher sweep but not with higher wingspan, which does not affect it ● Overall, higher wingspan decreases the longitudinal and directional stability of a small UAV while but assists in better lateral stability at high angles of attack. However, wing sweep changes assist in all types of stability. The conclusion is however that wingspan is more recommended in order to reduce trim requirements in air vehicles.

Cited references to follow up on	1. A. K. Jha and J. N. Kudva, “Morphing aircraft concepts, classifications, and challenges,” in *Proceedings of the Smart Structures and Materials 2004: Industrial and Commercial Applications of Smart Structures Technologies*, vol. 5388, pp. 213–225, International Society for Optics and Photonics, 2004. 2. I. Dayyani, A. D. Shaw, E. I. Saavedra Flores, and M. I. Friswell, “The mechanics of composite corrugated structures: a review with applications in morphing aircraft,” *Composite Structures*, vol. 133, pp. 358–380, 2015. 3. D. Lentink and R. de Kat, “Gliding swifts attain laminar flow over rough wings,” *PLoS One*, vol. 9, no. 6, Article ID e99901, 2014. 4. D. Lentink, U. K. Müller, E. J. Stamhuis et al., “How swifts control their glide performance with morphing wings,” *Nature*, vol. 446, no. 7139, pp. 1082–1085, 2007.
Follow up Questions	1. Do these same aerodynamics results apply to different weighted planes? 2. What occurs if the wing span is reduced to almost zero during a dive? 3. Do the materials used affect the results as much as size? 4. Could a UAV like this be produced and would it outperform non-morphing UAV? 5. Could wingspan morphing be made mechanical so when the plane attacks the wingspan is automatically adjusted without the need for a computer?

Patent #1: Heatsink for Electrical Circuitry

Source Title	Heatsink for Electrical Circuitry.
Source citation (APA Format)	Kedem, M. (2020). *U.S. Patent No. 10,748,837.* Washington, DC: U.S. Patent and Trademark Office.
Original URL	https://www.freepatentsonline.com/10748837.html
Source type	Patent
Keywords	1. Semiconductor: A 'nickname' for computer chips that consist of materials such as silicon which have a conductance between a metal and a nonmetal. 1. High Power Amplifier: A device used to transfer information or en electric signal at a very high level of power particularly for long distance or high-voltages 2. Integrated Circuit: A complex circuit printed onto a piece of silicon that constitutes a computer chip 3. GHz: An operating electrical oscillation frequency in a computer processor that exceeds one billion per second.
Summary of key points (include methodology)	This patent aims to solve the problem of important electronics such as high power amplifiers often overheating under load as transistors get smaller and smaller and traditional cooling methods become more and more inadequate. This design aims to use a PCM (phase change material) which would cycle directly onto the Integrated Circuit (IC) of a computer chip in order to more efficiently remove heat. This would consist of a pipe directly embedded into the IC that would run the PCM over it as a cycle occurs when the PCM evaporates (for example if water is used, computer chips can often reach the boiling point of 100 degrees Celsius), creates a higher pressure, and thus pushed itself out into a cooling vessel where it would cool in a porous medium or simply in a vesle, and then return into the substrate. This results in a cycle that is able to cool a computer chip by about 35 degrees Celsius if embedded from 55%-85% into the IC. However, this design is only meant for situations where traditional cooling is not enough as when the temperature returns to normal and below the PCM evaporation point the cycle stops as no additional pressure is created to push the PCM through the loop. So in summary, this design is a directly IC embedded PCM cooling system that is designed to use a self contained cycle to cool a computer chip in extraordinary situations.
Research Question/Problem/	How can electronic circuits be cooled most efficiently?

Need	
Important Figures	 ● ● This is an image of the side view of the design
Notes	● As computer transistors become smaller they need more cooling per area ● This device has a PCM (phase change material) channel embedded directly onto the silicon integrated circuit (IC) which allows for more efficient heat dissipation as the PCM then goes to a PCM vessel which cools and returns for more cooling ● The PCM can be as simple as a fluid like water ● As the PCM is evaporated, such as water, the increasing gas pressure will push more fluid towards the integrated circuit and itself will go through the pipe towards the PCM cooling vessel ● Once the PCM no longer evaporates because of the heat of the integrated circuit being low enough the cycle terminates. This means that it is only meant for short burst heating in extraordinary circumstances when traditional heating is not enough. ● This design can quickly decrease the temperature of the integrated circuit by up to 30 degrees Celsius. ● This design also contains a porous medium that allows PCM migration. ● The depth of the substrate in the IC in this design can range from 55-85%
Cited references to follow up on	US Patents: 1. 20160223269: <u>THERMAL MANAGEMENT FILMS CONTAINING PHASE CHANGE MATERIALS</u>

	2. 20140268579: <u>ELECTRONIC DEVICES ASSEMBLED WITH HEAT ABSORBING AND/OR THERMALLY INSULATING COMPOSITION</u> 3. 20140043754: <u>SYSTEMS, STRUCTURES AND MATERIALS FOR ELECTRONIC DEVICE COOLING</u>
Follow up Questions	1. What types of PCM's could be used? 2. Would this work consistently if a PCM with a low enough evaporation temperature was used? 3. What would occur if some of the PCM was to leak onto the IC? 4. Would a PCM that is non-conductive such as distilled-water have to be used? 5. Could a sudden temperature difference of the cycle start result in cracks in the IC?

Article #8: Modeling and Experimentation of New Thermoelectric cooler-Thermoelectric Generator Module

Source Title	Modeling and Experimentation of New Thermoelectric cooler-Thermoelectric Generator Module
Source citation (APA Format)	Teffah, K., Zhang, Y., & Mou, X.-long. (2018). Modeling and experimentation of new thermoelectric cooler–thermoelectric generator module. *Energies*, *11*(3), 576. https://doi.org/10.3390/en11030576
Original URL	https://www.mdpi.com/1996-1073/11/3/576/htm
Source type	Journal Article
Keywords	1. Thermoelectric cooler: A device that uses electricity in order to cool a substance 2. Peltier effect: When current is run through metals of two differently conductive metals and results in a temperature difference 3. Seebeck effect: When a difference in temperature between two metals of different conductance results in electric current 4. Joule heat: The heat produced when an electric current is run through a conductor
Summary of key points (include methodology)	In this article the author discusses that the thermoelectric effect has a wide range of applications in the real world whether it be for cooling or for electrical generation as it is environmentally friendly and simple. It was discussed that from 1960 to today, the efficiency of a thermoelectric generator has increased from around 5% to 20%. This results in the systems becoming more useful for cooling. Many designs that already exist combine a heatsink, a thermoelectric cooler and a thermoelectric generator all connected in series. This results in the heatsink being cooled and the hot side of the cooler's heat being turned into electricity. This is the design used here. The amount of voltage run through the thermoelectric cooler was changed, and the voltage that resulted from the generator as well as the temperature of the hot and cold plate was measured. The results indicate that when 1 V is run through a cooler the resulting temperature difference is 3.25 K while at 4 V the maximum cooling is achieved of 12.85 K. It was also found that for every volt supplied to the cooler the connected generator produced around 0.11 V. This

<table>
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<td>means that at 1 V 0.11 V were produced and at 5 V 0.5 Volts were produced, as the amount went down slightly as the voltage increased. Overall, this experiment demonstrated that a thermoelectric cooler can be used in order to cool many devices when connected to a heatsink, and any extra heat can be converted into electricity by a generator. This paves the way for all in one modules that would be able to make this process more efficient and the device cheaper.</td>
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<tr>
<td>Research Question/Problem/ Need</td>
<td>How can the Peltier effect be best utilized in order to cool items or create electricity?</td>
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<td>Important Figures</td>
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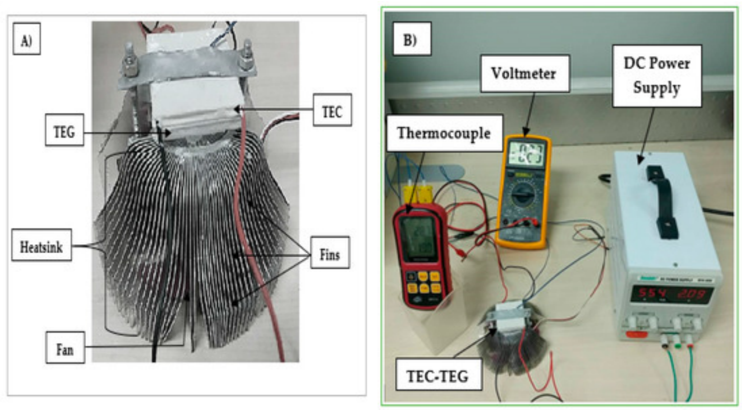
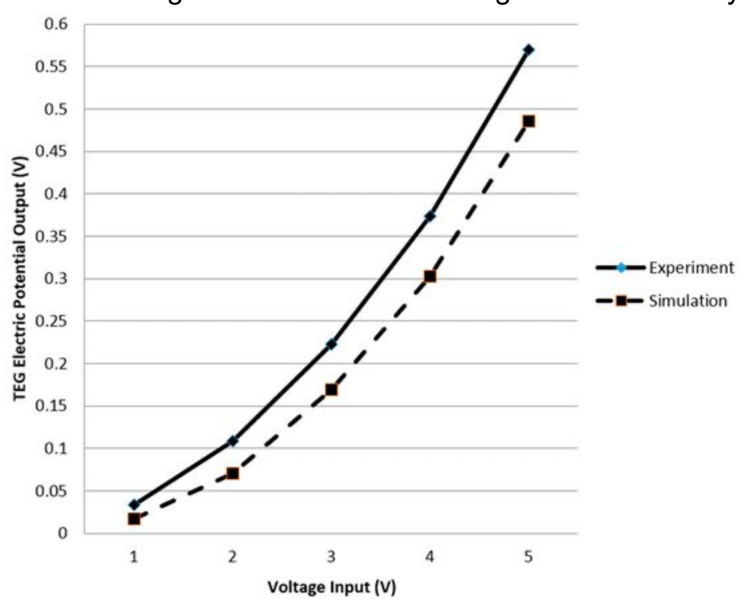


This the design that will utilize heat to generate electricity



This is the input versus output graph
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<tr>
<td>Notes</td>
<td>The author of this article connected a thermoelectric cooler, a thermoelectric generator, and a heat sink all in series so that</td>
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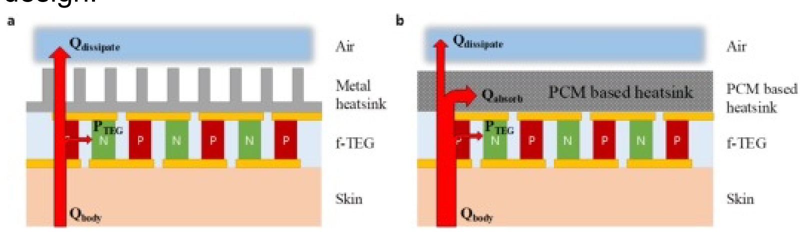
	the heatsink captures heat, the thermoelectric cooler cools the heatsink, and the thermoelectric generator captures some of the wasted heat and turns it into electricity ● The thermoelectric cooler was given a voltage from 1-5 volts ● Outside of research thermoelectric coolers are often used and are design by sandwiching semiconductors between thermoelectric coolers and an insulator such as ceramic plates ● A thermoelectric coolers works by applying electricity to two metals and thus one side gets hot and the other gets cold ● A thermoelectric generator works by applying a heat difference and then a current flows through the circuit ● From 1960 to 1990 the Seebeck effect allowed for devices with efficiencies of up to 5%, then from 1990-2010 the devices were 11-15% efficient, and up till now the efficiency can be up to 20% ● A Thermo electric cooler was bought and voltages from 1-5 were run through it in order to test the amount of cooling that the cool side can produce. ● At 1V the cold side goes from 300.15 K to 296.9 K, while it’s maximum cooling was at 4 V where the cold side went from 300.15 K to 287.3 K. The heat at 5 V is slightly hotter at 288.9 K because of Joule heat ● In this experiment the results were tested first in a simulation and then in an experimental setup ● If a thermoelectric generator is connected to the hot side of thermoelectric cooler the the temperature of the hot plate increases with the voltage given to the thermoelectric generator ● For every 1 V given to a thermoelectric cooler a connected thermoelectric generator makes 0.11 V while for every 5 V it makes 0.60 V ● Experimentally for 5 V given to a thermoelectric cooler it creates 0.5 V, thus giving an efficiency of 10%
Cited references to follow up on	1. Mahajan, R.; Chiu, C.-P.; Chrysler, G. Cooling a microprocessor chip. *Proc. IEEE* **2006**, *94*, 1476–1486. [**Google Scholar**] [**CrossRef**] 2. Prasher, R.S.; Chang, J.-Y.; Sauciuc, I.; Narasimhan, S.; Chau, D.; Chrysler, G.; Myers, A.; Prstic, S.; Hu, C. Nano and Micro Technology-Based Next-Generation Package-Level Cooling Solutions. *Intel Technol. J.* **2005**, *9*, 285–296. [**Google Scholar**] [**CrossRef**] 3. Simons, R.; Chu, R. Application of thermoelectric cooling to electronic equipment: A review and analysis. In Proceedings of the Sixteenth Annual IEEE Semiconductor Thermal

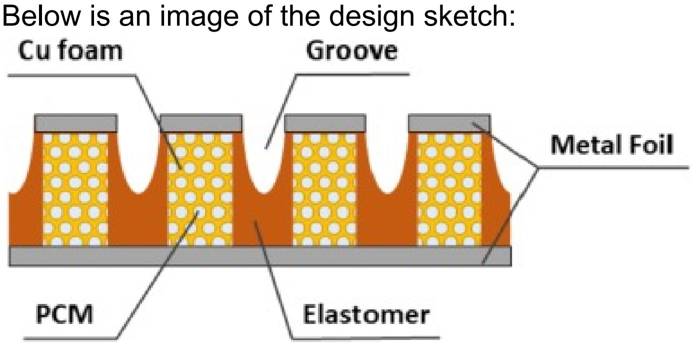
	Measurement and Management Symposium, San Jose, CA, USA, 23 March 2000; pp. 1–9. [**Google Scholar**]
Follow up Questions	1. What effect do different metals have on the Peltier and Seebeck effects? 2. Is there a limit when the Joule heat means that an increase in voltage will no longer create any additional cooling? 3. Can Joule heat be minimized? 4. Could the electricity created by the generator go directly back into running the cooler?

Article #9: Flexible heatsink based on a phase-change material for a wearable thermoelectric generator

Source Title	Flexible heatsink based on a phase-change material for a wearable thermoelectric generator
Source citation (APA Format)	Lee, G., Kim, C. S., Kim, S., Kim, Y. J., Choi, H., & Cho, B. J. (2019). Flexible heatsink based on a phase-change material for a wearable thermoelectric generator. *Energy (Oxford)*, 179, 12–18. https://doi.org/10.1016/j.energy.2019.05.018.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0360544219308813
Source type	Journal Article
Keywords	1. Wearable device : A device that can be wearable and usable for everyday purposes such as running, hiking, etc. 2. Electrocardiogram (ECG): A recording of someone's heartbeat for use in medical purposes 3. Elastomer: A polymer with elastic properties 4. Retention time of a PCM: How long a PCM (Phase change material) TEG (Thermo-electric generator) will continue operating at +/- 10% of a constant voltage.
Summary of key points (include methodology)	In this article the goal of the project was to create a heatsink that would allow for higher voltage generation by flexible thermo-electric generators that use the human body's heat to power devices. In order to do this the authors of the article decided to create a heatsink that is flexible similar to the thermo-electric generator (TEG) itself in order to better transfer heat from the skin to the device as flexible TEG's often have low voltage potentials. Thus, the authors created a flexible array of phase change material cubes (C18H38) and connected them via a flexible polymer with metal on top and cotton of the cubes. The PCM (phase change material) was filled in as thin tubes into a copper sponge in order to increase uniformity of heat distribution. The device was then tested using a flexible heater, a mannequin set on top of the heater, the flexible heatsink array on top of the mannequin and the generator on top of the heatsink. The heater was then set to 25 degrees Celsius and different changes were made to test the effectiveness of the heatsink. The results

<table>
<tr><td></td><td>indicate that the heatsink was effective in increasing the efficiency of the generator. When a design was tested without the PCM the voltage output was more than two times less and the time for which the voltage was produced went from 80 seconds with the PCM to 20 without it. It was also found that in order for the same voltage to be produced with a typical heatsink a heatsink made out of finned metal had to be twelve times higher and nine times heavier to produce 41.7mV while the PCM heat sink produced 48.2mV. It was also found that when going from 7g to 21g of the PCm in the design the length of operation increased from 30 seconds to 110 seconds. The results of this experiment indicate that this heatsink would increase the performance of flexible TEG’s in use for small scale body-heat powered devices. In the future the retention time of the voltage can be increased by increasing the ability of the copper foam to transfer heat.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can heatsinks best be used in order to improve the efficiencies of biothermal thermal energy generators?</td></tr>
<tr><td>Important Figures</td><td>

- Below is the design of the PCM based versus heatsink based design:
- 

- Below is an image of the design sketch:
- 

- When different amount of PCM were tested the data below resulted:

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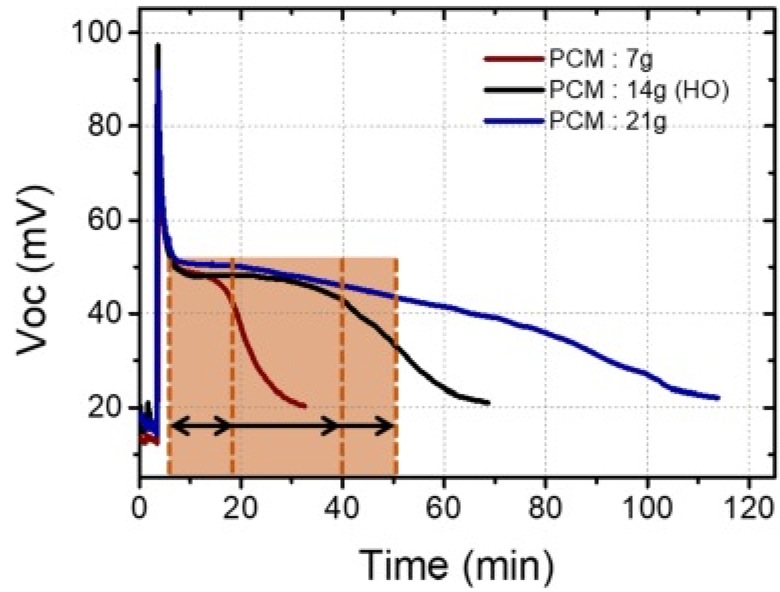
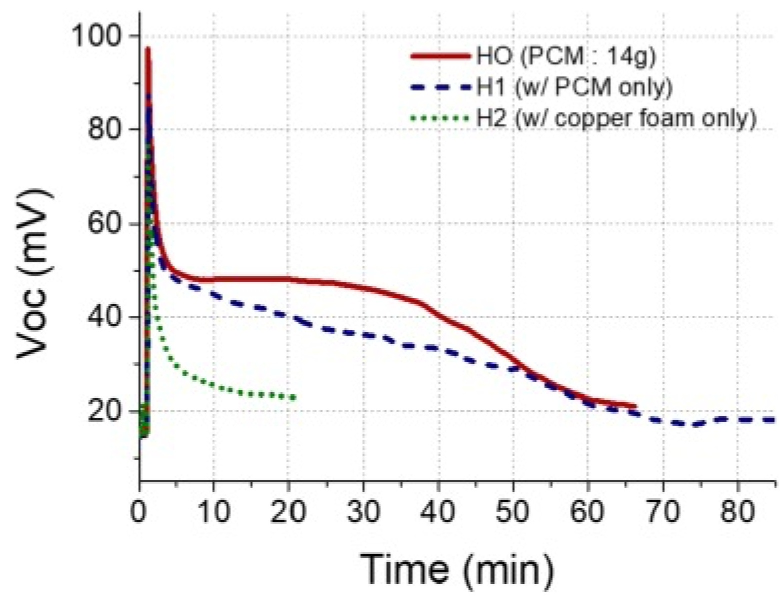
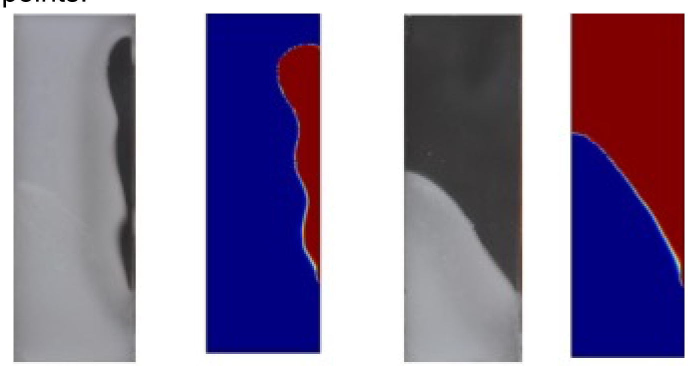
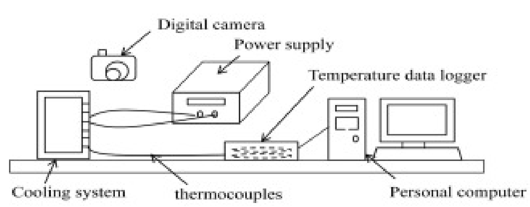
	•  • 
Notes	• The author argues that wearable devices allow for the human heat to be used in order to recharge devices • Wearable thermo-electric generators can be used to power low power devices such as electrocardiogram machines • In order for higher efficiency to be achieved a heatsink can be used to lower the amount of heat lost between the thermo-eelctric generator (TEG) and heat source and the TEG and air. • A traditional TEG can acquire an energy density of about 6.5 μW/cm2 under ideal conditions but it is often much lower in reality because of the uneven shape of contact caused by the human body shape. • Flexible heat sink can bridge the gap between the TEG and

	the skin and thus increase the TEG output so it can be used for more sophisticated electronics ● Different flexible heatsinks can be used with solid TEG's or can be used with flexible TEG's in order to get a completely flexible system, however the generation for these systems is still fairly low even for simple systems ● In this article the device constructed consisted of an array of small phase change material (PCM) cubes that would then be connected to an elastomer in order to be flexible. Then, this would be connected to the hot place of the flexible TEG and the results, presumably electric generation will be assessed ● When a flexible TEG is used the majority of the human body heat is not used and is instead dissipated into the environment ● Polymers and silica gel hydrates can be used as heat sinks but the water must be refilled and thus they can't last for long enough ● Phase change materials work well for heat sinks as they are able to store energy over a long period of time without changing in temperature ● For this experiment n-octadecane ($C_{18}H_{38}$) was used as it has a melting point of 28 degrees celsius ● Because the PCM has a low thermal conductivity copper foam was added in order to increase this ● Elastomer was added to the sides for flexibility and metal was added to the tops for conductivity ● Heater placed under simulation skin was used to test the design. ● When copper was not included in the testing the voltage produced slowly decreased ● A traditional heatsink was tested and the results of the traditional heatsink were about 6.5mV lower ● A heatsink with 200 cubes resulted in higher voltages than the same design with 50 cubes but has a lower thermal resistance so it is more powerful ● For this project the voltage during the retention time was tested ● A traditional heatsink has to be 12 times higher and 9 times heavier in order to achieve the same voltage production ● When the amount of PCM was increased to 21g the retention time rose from 12 to 44 minutes
Cited references to follow up on	1. S.J. Kim, J.H. We, B.J. Cho. A wearable thermoelectric generator fabricated on a glass fabric. Energy Environ Sci, 7 (6) (2014), pp. 1959-1965. https://doi-org.ezpv7-web-p-u01.wpi.edu/10.1039/C4EE0024

	2C 2. M. Hyland, H. Hunter, J. Liu, E. Veety, D. Vashaee Wearable thermoelectric generators for human body heat harvesting Appl Energy, 182 (2016), pp. 518-524 https://doi-org.ezpv7-web-p-u01.wpi.edu/10.1016/j.apenergy.2016.08.150
Follow up Questions	1. Could other PCM's be used for better voltages? 2. Could this same design be used for connection with the air? 3. Could an alternative to copper foam provide better results? 4. Does copper foam result in lower conductance because of air gaps?

Article #10: Experimental study of the cooling performance of phase change material with discrete heat sources – Continuous and intermittent regimes.

Source Title	Experimental study of the cooling performance of phase change material with discrete heat sources – Continuous and intermittent regimes.
Source citation (APA Format)	Gharbi, S., Harmand, S., & Jabrallah, S. B. (2017). Experimental study of the cooling performance of phase change material with discrete heat sources – Continuous and intermittent regimes. *Applied Thermal Engineering*, 111, 103–111. https://doi.org/10.1016/j.applthermaleng.2016.06.109.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S1359431116310213
Source type	Journal Article
Keywords	1. Discrete Heat Source: A separate and self-contained heat source such as a computer chip 2. Phase Change Material (PCM): Previously defined 3. Intermittent periodic heat flux: When a certain substance is subject to short bursts of heat with time in between 4. Critical Temperature: The temperature at which continued operation can cause damage to electrical components 5. Critical time: The time it takes to reach critical temperature for a computer component
Summary of key points (include methodology)	In this experiment a chamber with three heat sources was tested in order to find out the ideal parameters of heat flux distribution for critical time optimization. The goal was to increase the critical time of the phase change material (paraffin wax) in order to make the performance of the system better. In order to do this images were taken of the cavity used for the experiment in order to determine how the heat flux affected the temperatures and melting of the PCM in different areas of the chamber. The results indicate that with three evenly vertically spaced distinct heat sources the amount of liquid PCM is first evenly distributed but then becomes higher at the top of the chamber as convection begins when the three liquid sections become large enough to be connected. Thus, the heat rises and the highest chip becomes hot quickest and thus richest its critical temperature quicker. As a result the same design was tested where the heat flux was not uniform within the three chips and where the

	majority of it went to the bottom two chips. This increased the critical temperature and resulted in a lower temperature for the top chips and thus allowed for long term operation. Finally it was also found that if the device is being used to cool high power and thus high heat devices that are used in cycles the more cycles are done for the same amount of work the longer the critical time becomes. This means that using 5-7 cycles for the same amount of computing results in lower temperatures than using 2-4 cycles for the same amount of work. Overall this experiment allows for further information of how PCM's can better be positioned and how heat flux can better be controlled to allow for increased low temperature operation times.
Research Question/Problem/ Need	How can the critical time of a PCM based cooler be increased through changing the geometric design of the cooler?
Important Figures	• The theoretical and experimental melting after different time points:  (a) (b) (a) (b) • 3900s 12000s • The design used is attached below:  • (a)

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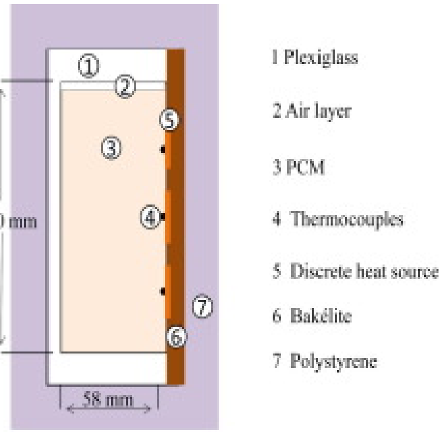
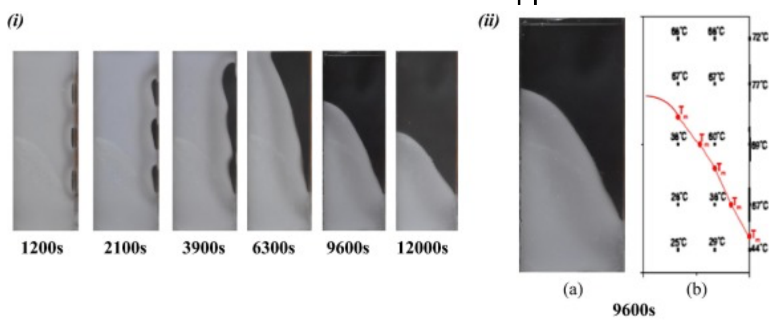


(b)
When there are three heat sources it can be seen that while the amount of heat emitted by each is the same the largest amount of melted PCM is towards the upper one:



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<tr>
<td>Notes</td>
<td>

Phase change materials have been used in order to cool devices during intermittent heat spikes
Paraffin wax has been used for the above mentioned purpose
PCM’s work well when combined with traditional cooling methods
The best distance at which to keep different discrete heat sources it related to the golden ratio
Cavities can often be used for heat transfer
When a rectangular cavity filled with a PCM is modeled connected flush to three heat sources the most intense amount of heat is in the center one while the top and bottom heat sources are actually lower because those areas are being used for melted PCM and the thermal conductance there is lower
Past literature has mostly focused on how to space out the heat source and the design of the PCM cooler
In this experiment the critical time is attempted to be extended by changing the spacing of the PCM and the 3 distinct heat source used for testing

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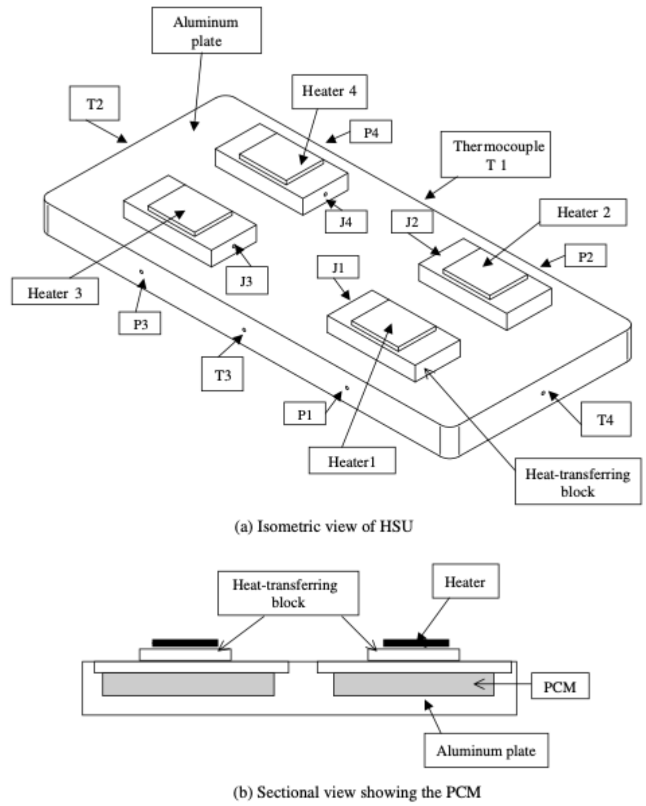
	● The PCM used in this experiment was plastic paraffin ● 21 thermocouples were distributed throughout the system to record temperature ● An expect reason for this is that the hot liquid is convected upwards and thus keeps the upper part hotter while the heat leaves the bottom ara and leaves it cooler ● The PCM is eventually unable to keep the chips cool and an increase in temperature occurs ● This increase occurs once the sections of melted PCM conjoin ● With three heat sources of uneven temperature when the majority of temperature is coming from the top heat source the quickest critical temperature is reached while when the bottom two release the most heat the longest time until critical temperature is achieved ● The longest time for critical temperature occurred when the bottom parts of the chamber had the most heat flux ● When a cyclical heat cycle is used it is found that the change in temperature keeps increasing until all PCM is melted at which point it stabilizes ● The more cycles were done for the same amount of computing the longer it worked before reaching critical temperature ● The best heat partitioning with three sources is for long operation equally between the two bottom ones and for short term changing it between the two periodically with one slightly more at a time
Cited references to follow up on	1. R. Kandasamy, X. Wang, A.S. Mujumdar. Application of phase change materials in thermal management of electronics. Appl. Therm. Eng., 27 (2007), pp. 2822-2832. ArticleDownload PDFView Record in ScopusGoogle Scholar 2. F.L. Tan, C.P. Tso. Cooling of mobile electronic devices using phase change materials. Appl. Therm. Eng., 24 (2004), pp. 159-169. ArticleDownload PDFView Record in ScopusGoogle Scholar
Follow up Questions	1. What would happen if there were two chambers? 2. Could the PCM itself be cooled or would using simply air cooling directly on the electronic be more efficient? 3. Would the results change depending on the PCM used? 4. Would a PCM with a higher melting point work better for cooling electronics?

Article #11: Cooling of mobile electronic devices using phase change materials

Source Title	Cooling of mobile electronic devices using phase change materials
Source citation (APA Format)	Tan, F. L., & Tso, C. P. (2004). Cooling of mobile electronic devices using phase change materials. *Applied Thermal Engineering*, *24*(2-3), 159–169. https://doi.org/10.1016/j.applthermaleng.2003.09.005
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S1359431103002837
Source type	Journal Article
Keywords	1. Personal Digital Assistant (PDA): Any electronic device that assists someone in something 2. Heat Storage Unit (HSU): A source of heat, usually some sort of simulated heat source used to test thermodynamics of some design 3. Phase change material (PCM): Previously defined 4. Heat dissipation: The movement of heat from a hot object to a cold object 5. Thermocouple: A device made of two pieces of different metals used to measure temperature
Summary of key points (include methodology)	In this experiment a mobile PDA device cooling was tested using four heaters evenly placed above four aluminum chambers filled with PCM. This heat flux from each heater was then changed independently in order to find what wattage distribution allows for the most efficient cooling. The cooling of the system was diminished and the temperature of the four areas began to increase once the PCM had all melted and thus the goal was to ensure that the PCM did not melt over the 2 hour period tested. The four orientations tested were even distribution of heat with and without PCM, and also diagonal increased/decreased heat distribution as well as uneven heat distribution in which one heater supplies more heat than any of the other ones. The results indicate that even with the same total amount of heat flux the orientation of that heat flux within the four heaters can result in different time to critical temperature. It can also result in different total amounts of heat increase to the components. Finally, it was determined that generally the greater the amount of heat transferred the greater the temperature of the chips becomes. It was also found that the more PCM is used the longer it can cool the chips

<table>
<tr><td></td><td>before it reaches maximum operating temperature. Overall these results help indicate the effect that cooling block placement has on the potential of cooling systems.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can the heat storage unit best be oriented inside of an electronic device to allow for optimum cooling?</td></tr>
<tr><td>Important Figures</td><td>

- The device is configured as shown below:



(a) Isometric view of HSU

(b) Sectional view showing the PCM

Fig. 1. Heat storage unit (HSU) containing the PCM.

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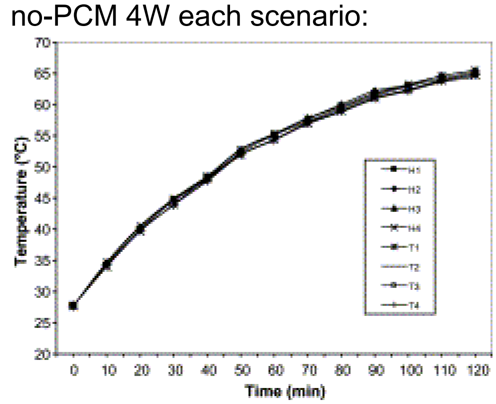
- Below is the image for the graph of temperatures for the no-PCM 4W each scenario:



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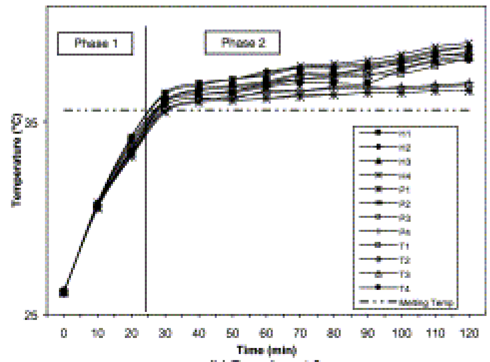
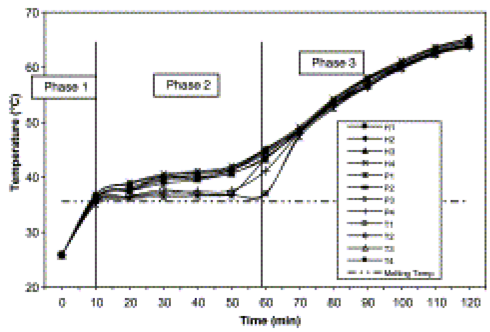
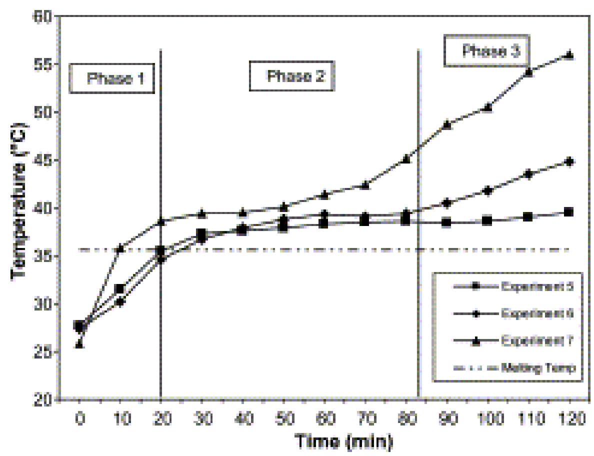


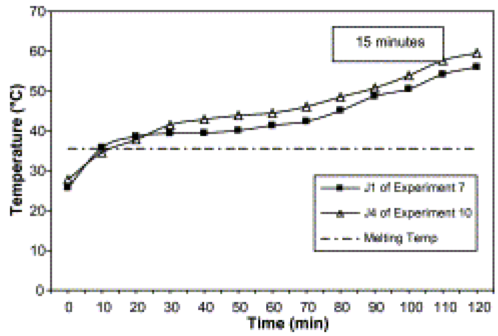
(b) Experiment 3



- (b) Experiment 4
- With the diagonal configuration the following results are achieve:



- Even if the total power dissipated is the same the orientation can change the temperature until maximum temperature is reached:

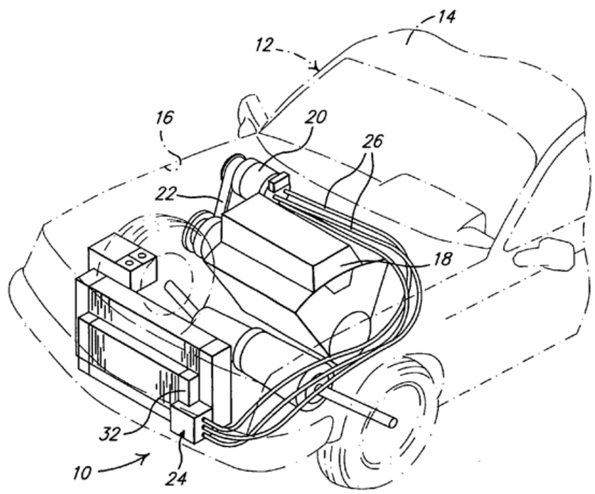
	• 
Notes	• THere is a heat storage unit inside of the mobile electronic device filled with a PCM • The PCM used is n-eicosane which is chemically related to paraffin wax • The goal is to keep the chips under 50 degrees Celsius for 2 hours of continuous operation • The electrical resistance of electrical components is what results in heat generation • Some devices can combust if they get too hot • As this was written in 2003 it isn't very up to date with today's devices • The molten PCM can release heat when the device is idle, thus going back to its initial state • The PCM maintains its temperature until it is fully melted because by the basics of chemistry phase changes do not result in temperature changes • It is needed for low enough temperatures to be kepts that the PCM does not completely melt otherwise its temperature will increase and so will the temperature of the computer chip • A model made by Marongiu and Clarksean used salt that melted and then was convected into contact with air where it cooled • A heat storage unit can contain simply PCM inside of an aluminum chamber • One of the more important characteristics was found to be the melting point of the PCM in previous studies • The melting point of the PCM used is 36 degrees Celsius • There are four PCM cavities and four thermocouples • There were four tests run each time changing the power from 1-4 W for each heater. The four experiments were uniform with PCM, uniform without PCM, uniform diagonal with PCM, and non-uniform with PCM • Thermal paste was used when the heaters were put onto the PCM cavities • The total time of each experiment is 2h • With the experiment of consistent 1-4 W each with PCM the

	results show that for the 1 and 2 W each scenarios the temperature stayed completely the same the whole time as all of the PCM did not melt and for 3 and 4 W respectively the temperature change was 3 and 9 degrees Celsisus after the PCM totally melted ● The more PCM is used the longer the chips can be kept within serviceable temperature ● For the non-uniform distribution experiment the heat dissipation of one heater is set higher while the rest are equal ● The results of this experiment indicate that there is no tangible benefit to this design as there is a much higher temperature in the pocket with the highest set temperature ● Overall the conclusion is that different configurations result in different temperatures even if the total heat dissipation is equal, and additionally that the more PCM is used the greater the cooling potential becomes
Cited references to follow up on	1. N. Leoni, C.H. Amon, in: Transient Thermal Design of Wearable Computers with Embedded Electronics Using Phase Change Materials, HTD-Vol, 343, Heat Transfer Conference, vol. 5, ASME, 1997. 2. D. Pal, Y.K. Joshi, Application of phase change materials (PCMs) to the passive thermal control of a plastic quad flat package: effect of orientation of the package, in: Thermal Management of Electronic Systems II, Kluwer Academic Publisher, Leuven, Belgium, 1997, pp. 227–242.
Follow up Questions	1. Do the same principles apply to a modern smartphone? 2. Could this be tested with different PCM’s? 3. What would happen if there were only two heat sources? Ten? 4. What would happen if the heat cavity surrounding metal was changed from aluminum?

Patent #2: Phase-change cooling system

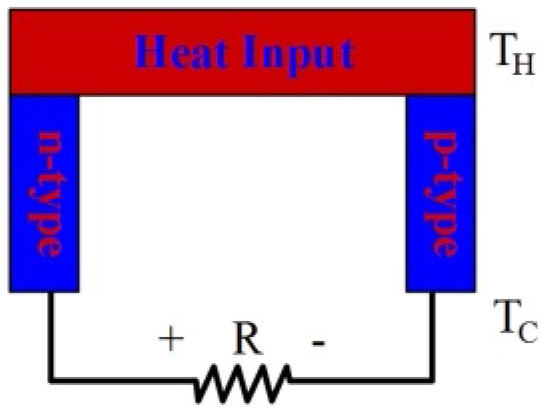
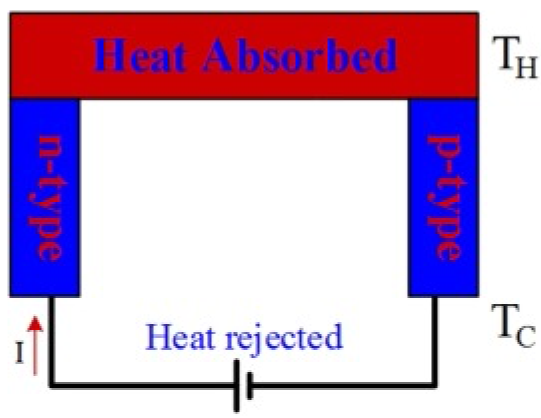
Source Title	Phase-change cooling system
Source citation (APA Format)	Albertson, W.C. (2006). Phase-change cooling system. (United States Patent No. 7104080). US Patent and Trademarking Office.
Original URL	https://www.freepatentsonline.com/7104080.pdf
Source type	Patent
Keywords	1. Phase change material (PCM): Previously defined 2. Condenser: A device that is used to condense something from a gaseous form to a liquid form, aka. condensing a gas 3. Electronic control device: A device used to control the various functions of a car such as the interlock brake system, timings, etc. 4. Alternator: An electric generator that produces alternating current in a car utilizing extra energy from the engine 5. Coolant pump: A pump used to circulate fluid around a car's cooling loop so that the engine and its various parts don't overheat
Summary of key points (include methodology)	This patent describes the design for an electronic control device in a vehicle. These devices are used to control multiple aspects of cars and can often overheat causing problems with the car's control and thus safety concerns. There do exist designs for cooling these devices but they are often energy parasitic or combustible. The goal of this was to use the already existing coolant loops in the car to cool these devices. This design uses a condenser which is connected to the air conditioning system in the car to transform a coolant into gas through the exchange of heat, have it convect and then condense, thus cooling the device through sensible heat transfer and through phase change heat transfer. This device would be part of the already existing coolant loops and would not be detrimental to the cooling of other parts of the car or energy parasitic. Thus, this patent describes a cheap, efficient and safe design that can be used to cool control devices in cars.
Research Question/Problem/ Need	How can the phase change of vehicle coolant be combined with controls from an electronic control device to effectively cool a car?
Important Figures	Inventor: Albertson, W.C.
Notes	● This device is made to cool an electronic control device in a

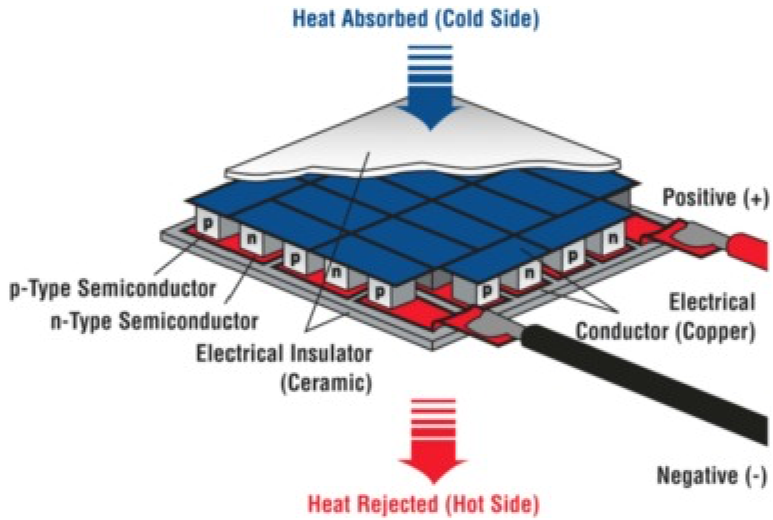
	car ● For this design a phase change material cooling design was used ● The phase change occurs when the coolant in the coolant loop is changing phases ● Many control devices for cars can get hot during operation, and when they are cooled using the coolant loop they require additional energy from the alternator for this ● Sometime self contained devices for cooling control devices can be combustible or ineffective of can perhaps be parasitic in terms of energy if needing in circulation energy ● This device aims to create a cheap, non-combustible and self-contained control device cooling package ● In order to cool the device the control device communicates with the air conditioning system to use the air conditioning refrigerant to cool the device ● Inside of the condenser the refrigerant is a gas and rises, then turning into a liquid and moving in order to cool devices ● In this case aluminum is used for the casing of every part ● The cooling effect occurs because of the sensible heat difference between the coolant and the chipset but also to a lesser extent by the phase change of the coolant ● The phase change liquid coolant becomes a gas, rises and then condenses, this condensation causes it to cool the area where the control device is located, and then the vapor condenses and returns ● The goal is to create a lower temperature than the initial one ● The highest coolant temperature should be 70 degrees Celsisu and the maximum temperature allowable to the control device is around 106 degrees Celsius
Cited references to follow up on	● Below is an image of the design:

	 FIG. 1. •
Follow up Questions	1. Would the movement of the car affect the efficiency of this device? 2. What coolant would be used for this? Would it be a typical AC coolant? 3. Would a typical AC coolant have too high of a condensation temperature? 4. Could this be applied to other heat releasing devices?

Article #12: Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials.

Source Title	*Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials.*
Source citation (APA Format)	Pourkiaei, S. M., Ahmadi, M. H., Sadeghzadeh, M., Moosavi, S., Pourfayaz, F., Chen, L., Pour Yazdi, M. A., & Kumar, R. (2019). Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials. *Energy (Oxford)*, 186, 115849–. https://doi.org/10.1016/j.energy.2019.07.179
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S036054421931521X
Source type	Review Article
Keywords	1. Non-equilibrium thermo-dynamics: an area of thermodynamics that deal not with systems in thermal equilibrium but rather systems that are not in equilibrium and that require equations to describe thermal movement 2. Radioisotopic: A material that produces a radioactive isotope 3. Photovoltaic: A material that produces electricity when exposed to light 4. Micro-electromechanical systems: Systems that are part of microscopic devices that contain moving parts
Summary of key points (include methodology)	In this review article the authors aim to review the uses of thermoelectric generators (TEGs) and coolers (TECs), as well as their evolution over time and their potential future and current uses. They begin by discussing the advances in the utilization of TEGs and TECs. They discuss that the devices function via the Seebeck and Peltier effects, via which two metals of different resistance result in a temperature difference or current depending on whether a current is supplied or a heat difference is supplied. Then the authors discuss the current areas for improvement. Most often TE (Thermoelectric) devices utilize ceramics, polymers, or semiconductors for electrical generation. These are areas in which improvement is being made, but one of the most common materials is bismuth-tellurium semiconductors. Then the application of TEs is discussed. They are often used but one of the most important drawbacks of them is their

	low efficiency. Thus they can be used in areas where there is waste heat, such as in cars or power stations but in other scenarios they are often too inefficient, such as for car cabin cooling. However, if they are included in other devices they can be useful. Also, their efficiency is improving over time and they can consistently improve and thus become more useful as research progresses.
Research Question/Problem/ Need	What data has been gathered to best allow thermo-electric generators to become more useful and efficient?
Important Figures	1. How a TEG functions:  2. How a TEC functions:  3. More complicated TEG example:

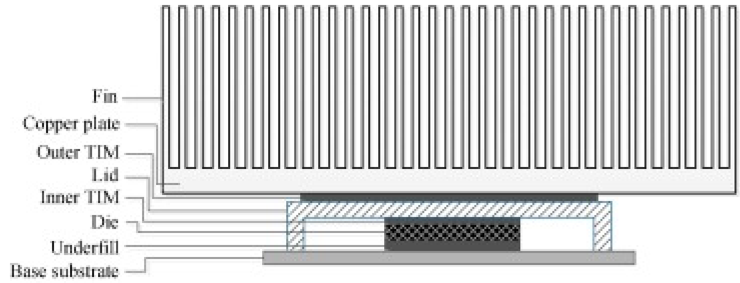
	 4.
Notes	● Thermoelectric generators are generally long lasting as they have no moving parts ● They are also environmentally friendly as they use sustainable and non-toxic materials, and contain no fluids ● This article is a review article and covers previous research ● The name for the thermo-electric effect is the Seebeck effect ● The higher the voltage between two metals, the higher the temperature difference ● A quantum effect titled the Fermi effect is the suspected reason for this effect ● These devices can operate steadily for 100,000 hours ● Semiconductors, ceramics, and polymers are the most used materials in TE (thermoelectric) devices ● Often the most complicated material for Thermo-electric materials is polymers as they can be expensive, difficult to manufacture, and toxic. They also have to be conductive ● In the past experiments have been done to use polymers that use body heat for electrical generation ● Oftentimes in order to improve materials impurities are added that increase properties ● Bismuth-Tellurium is a promising area of materials ● Thermo-electric coolers (TEC’s) have a maximum coefficient of performance, so they are most useful at wattages under 25W ● Thermoelectric coolers can be used to produce water from humid air ● The layout of the hot plate of thermoelectric generators (TEG) and coolers (TEC) has the largest effect on the coefficient of performance

	TEC's can be used to keep electronic devices at temperatures BELOW the ambient temperature - If TEC's are used with a water/air cooled system they can cool about 207 Watts - TEC's used for air conditioning require about 5 times more input power for the cooling output as a traditional compressor powered system - Photovoltaic cells can be used in combination with TEG's and TEC's - TEG's can also be made foldable - TEG's can be used to harvest exhaust or engine heat in cars - PCM's can be used to increase the power generation time even after the heat source is reduced - Combining multiple generation sources and TEG's can increase power output - TEC's can be used in heat sinks to boost the performance by up to 110%
Cited references to follow up on	1. F.J. DiSalvo. Thermoelectric cooling and power generation. Science, 285 (1999), pp. 703-706, 10.1126/SCIENCE.285.5428.703 2. S. Riffat, X. Ma. Thermoelectrics: a review of present and potential applications. Appl Therm Eng, 23 (2003), pp. 913-935, 10.1016/S1359-4311(03)00012-7
Follow up Questions	1. If TEG's and TEC's are made enmass would this create another source of pollution if dangerous materials are used? 2. Could TEG's be created to use the sun as a heat source and the earth as a cool plate? 3. Do TEG's turn heat into electricity or simply move heat and thus generate electricity? 4. If TEC's were used for cooling would this result in the need for heatsinks, as traditional AC units utilize air and thus can blow out the hot air and don't need solid heat sinks?

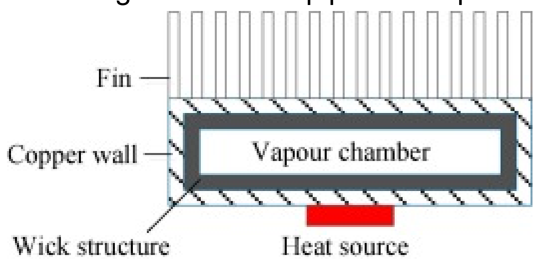
Article #13: Energy saving potential of using heat pipes for CPU cooling

Source Title	*Energy saving potential of using heat pipes for CPU cooling*
Source citation (APA Format)	Wang, Y., B., Zhu, K., Li, H., He, W., & Liu, S. (2018). Energy saving potential of using heat pipes for CPU cooling. *Applied Thermal Engineering*, 143, 630–638. https://doi.org/10.1016/j.applthermaleng.2018.07.132
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S1359431118302953
Source type	Research Article
Keywords	1. Heat Pipe: A closed pipe that utilizes a cycle of fluid condensation and evaporation for thermal energy movement 2. Thermal interface material (TIM): A materials that is inserted between two devices that is used to increase the heat flux between them 3. CPU: central processing unit 4. Micro channel: When narrow channels are etched into CPU dies that convect a liquid for cooling 5. Jet impingement: A forced convection that results in very high flow rates of a substance
Summary of key points (include methodology)	In this article the goal was to test whether or not heat pipes would be useful in order to cool computers more efficiently and thus save energy. For this six different designs were built each unique, with one of them being a standard aluminum heatsink. These were the tested with an artificial heatsink and a ceramic insulation plate inside of a wind tunnel which provided a simulated air flow. The energy needed to keep the CPU under 70 degrees Celsius would indicate which of the size designs was the most effective. The results show that the design with multiple aluminum heat sinks and a large amount of heat pipes extending towards both sides of the heatsink resulted in the best performance and a fan electrical demand of 66.2% lower, and a CPU electrical demand of 25.3% less. However, another design with less heat sinks had the best cooling to weight performance. All of this together shows that heat pipes are capable of reducing energy inputs needed for CPUs and CPU cooling, and are able to be integrated directly into heatsinks. However, because this article used a simulated heat, a real CPU could be tested in the future.
Research	Do heatsink embedded heat pipes lower the cooling potential needed

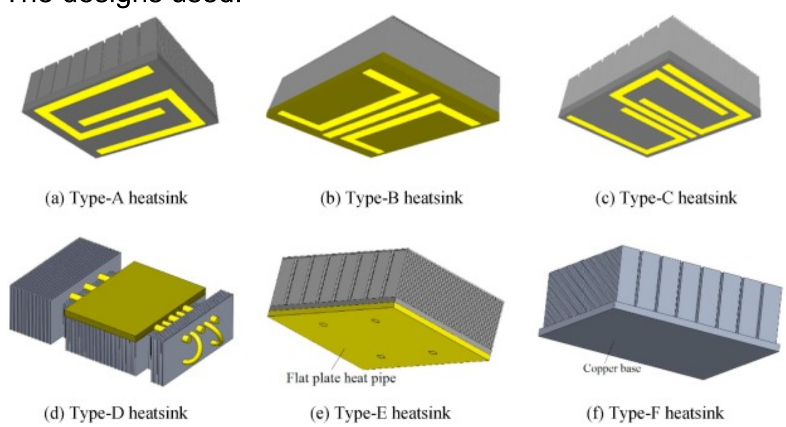
<table>
<tr><td>Question/Problem/ Need</td><td>from air cooling methods in computer cooling designs?</td></tr>
<tr><td>Important Figures</td><td>
1. An image of the most common cooler design:



2. The design with a heat pipe and copor chamber:



3. The designs used:



4. The results:
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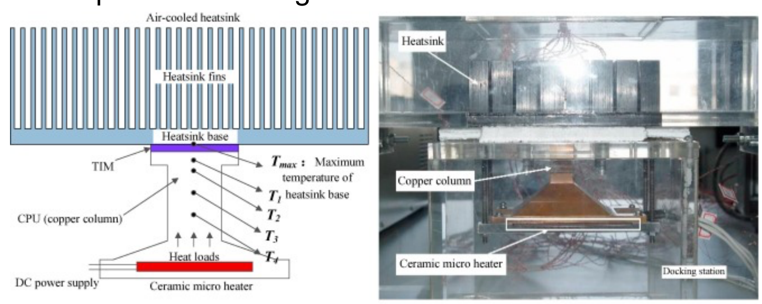
</table>

Heatsink type	Base material	Fin material	Number of embedded heat pipe	Working fluid (heat pipe)	Fluid filling ratio (heat pipe)	Housing material (heat pipe)	Weight (g)	Dimension (mm) (Length × Width × He
Type-A	Aluminum	Aluminum	2	Water	50%	Copper	560	130 × 100 × 43.6
Type-B	Aluminum	Aluminum	3	Water	50%	Copper	595	130 × 100 × 43.6
Type-C	Aluminum	Aluminum	3	Water	50%	Copper	580	130 × 100 × 43.6
Type-D	Copper	Aluminum	5	Water	50%	Copper	880	177 × 100 × 43.6
Type-E	Flat plate heat pipe	Aluminum	Flat plate heat pipe	Water	60%	Copper	680	130 × 100 × 43.6
Type-F	Copper	Aluminum	0	–	–	–	851	130 × 100 × 43.6

5. The experimental design:

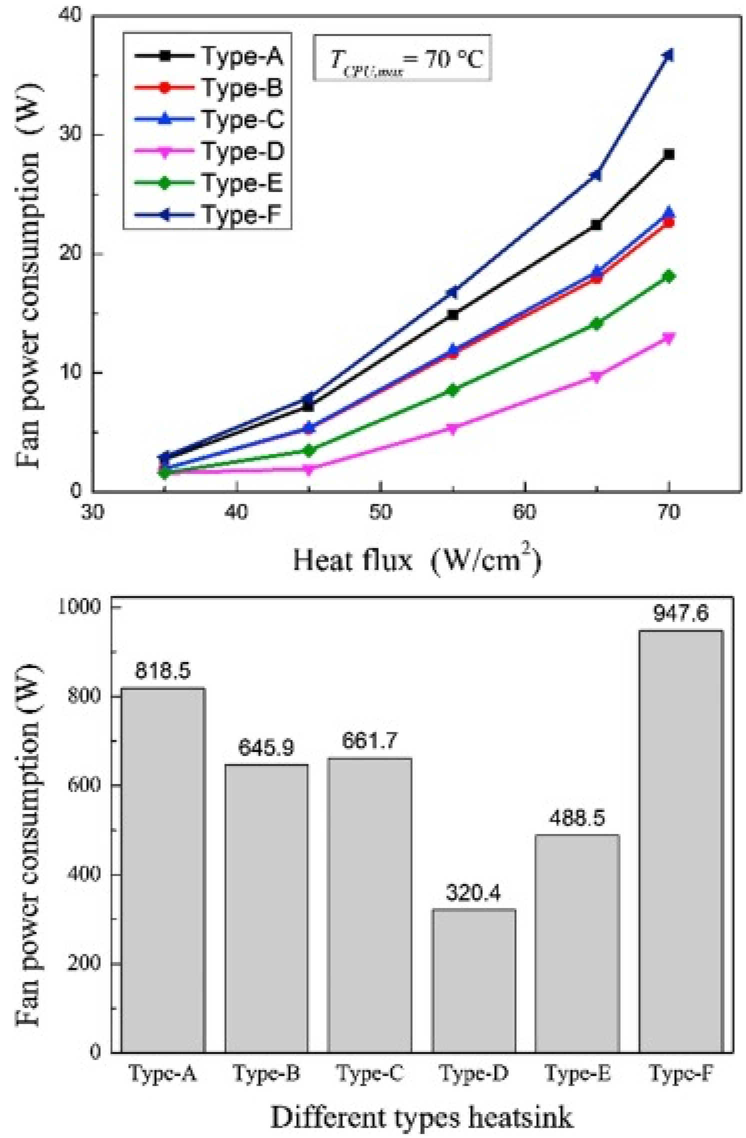


(a) (b)

6. The results of the experiment:

	Type-A	Type-B	Type-C	Type-D	Type-E	Type-F
Air velocity	v = 3.0 m/s					
Weight of the heatsink (g)	560	595	580	880	680	851
Thermal resistance (°C/W)	0.2	0.18	0.19	0.15	0.17	0.22
Cooling capacity (W)	132	147	139	176	155	120
Overall performance (g/W)	4.24	4.05	4.17	5	4.39	7.09

7. Power consumption graph:

	 8.
Notes	• As the operating temperatures increase the failure rates increase • Data centers used more than 1.4% of global electricity in 2010 • Most common computer coolers utilize a fan on top of a finned aluminum heat spreader, with a thermal interface materials and heat spreader on the CPU • Two methods for increasing cooling capacity are increasing the size of the fins and increasing the velocity of the air over the fins • Because the size of the CPU lid is much smaller than the aluminum heatsink it is often not able to fully utilize it • Because of this, temperature gradients are created which can harm the CPU

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Jet impingement combined with microchannels in the silicon can increase cooling potential as well
Heat pipes can also be used, and consist of a tube in vacuum and lined with a porous substance, and filled with water, such as when the water boils at a lower temperature because of the vacuum it rises, cools on the heat fins connected to the heat pipe, and condenses, thus working over and over again
If a copper block was used the temperature difference was 50 degrees Celsisus less, and if a flat plate heat pipe was used the temperature difference was 15 degrees Celsius less
If the heat pipe is integrated directly into the die it is cheaper and smaller, as well as more effective with a cooling capability of 60 W
If they are embedded horizontally then the cooling capacity rises to 140 W
If the heat pipe shape is change, the cooling capacity changes
If two heat pipes are embedded the thermal resistance is lowered by 11.1% and if four are used it is reduced by 25.2%
If fans have to work less then less energy is used
Water can be used as the working fluid
Multiple designs were tested by being placed into a wind tunnel with an artificial 105 W heater with a 50 W conductance, with thermocouples inside of the device
The more heatpipes there were the higher the heat flux and the more even the heat distribution
Type E resulted in a fan power consumption more than 50% lower
The higher the temperature of a chip the more energy is needed, and thus the higher the energy, etc., etc.
Type E reduces the fan power consumption by 48.4%, and type D by 66.2%
Type B has the lowest ratio of weight to cooling capacity
Type D reduces the CPU power consumption by 25.3% as well

</td></tr>
<tr><td>Cited references to follow up on</td><td>

Khosrow Ebrahimi, G.F. Jones, A.S. Fleischer.
A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew. Sustain. Energy Rev., 31 (2) (2014), pp. 622-638
Bin Sun, H. Liu. Flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU heat radiator. Appl. Therm. Eng., 115 (2017), pp. 435-443.
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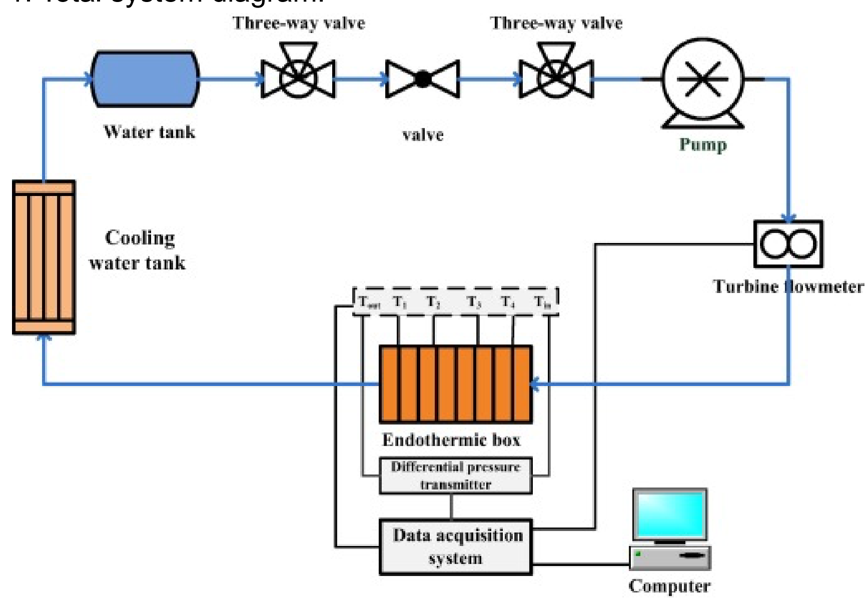
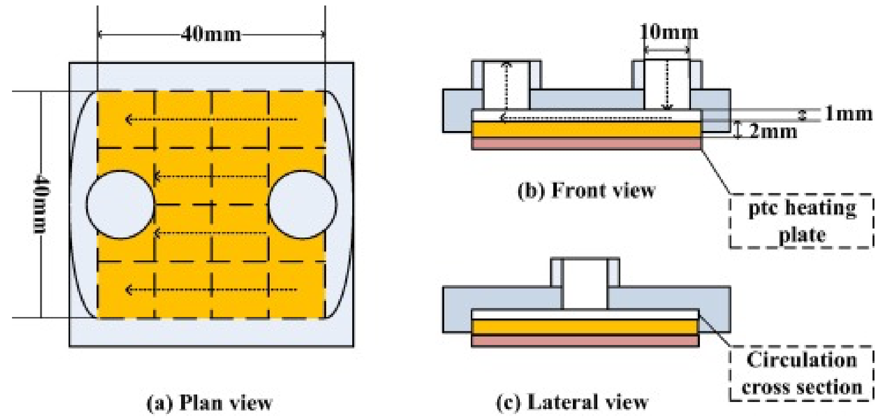
Follow up Questions	1. Will the results be different with a real CPU? 2. Why do CPUs use more temperature if they are hot? 3. Do fans even use a significant amount of electricity? 4. Could a thermoelectric generator be used instead? 5. Does this provide any benefit in cooling? 6. What is the cost difference?

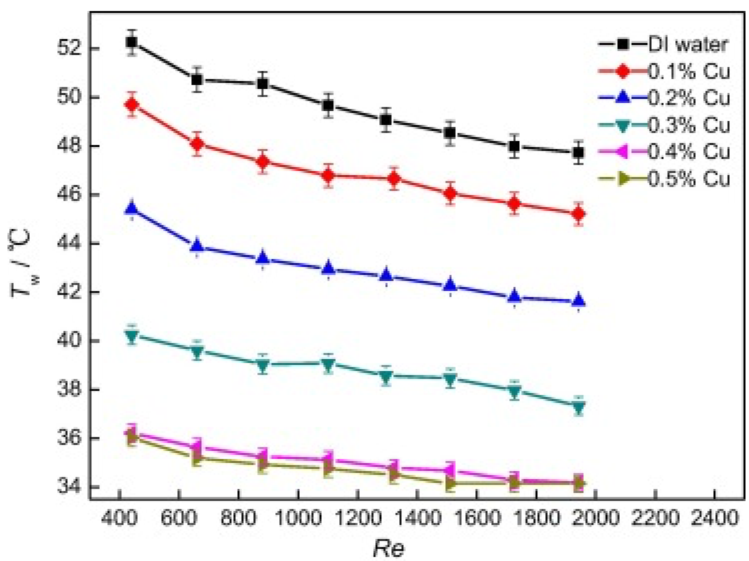
Article #14: Flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU heat radiator

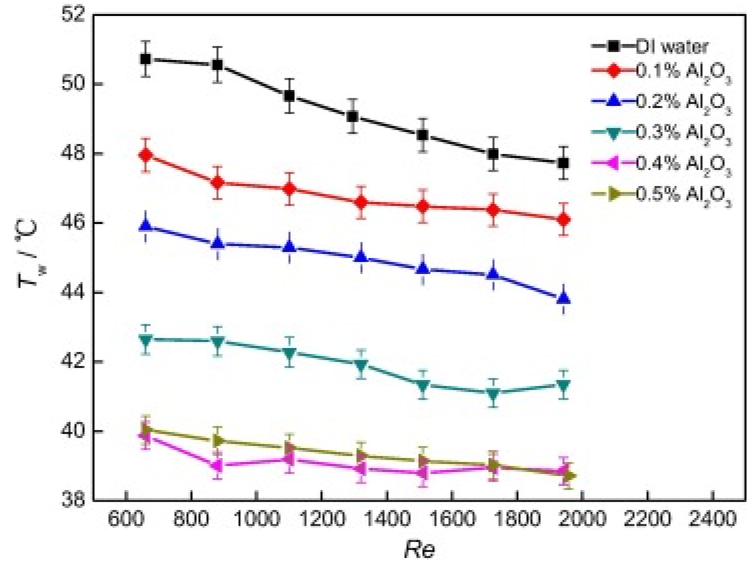
Source Title	*Flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU heat radiator*
Source citation (APA Format)	Sun, B., & Liu, H. (2017). Flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU heat radiator. *Applied Thermal Engineering*, *115*, 435–443. https://doi.org/10.1016/j.applthermaleng.2016.12.108
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S135943111634368X
Source type	Journal Article
Keywords	1. Nanofluid: A fluid containing nano-particles 2. Nanoparticle: Particles with a diameter equal to or less than one nanometer 3. Deionized: Something which lacks ions 4. Convective heat transfer: The transfer of heat through the movement of liquids 5. Reynold's number: A number which allows for the prediction of liquid flow in different patterns 6. Laminar flow: The movement of a liquid in a smooth paten where there are layers of liquid flow past each other without mixing
Summary of key points (include methodology)	In this article the goal was to test whether or not nanofluid dispersions would improve the cooling performance of liquid cooling radiator based computer coolers. For this experiment they used Cu and Al_2O_3 for nanoparticles, each of which were dispersed in deionized water and used sodium dodecyl benzene sulfonate to disperse the nanoparticles. They then built a CPU heat box by using a pump to pump this nanofluid, an endothermic cooling source to cool it, thermocouples to record temperature, and After this they tested mass percentages of each of the nanoparticles separately from 0.1-0.5% and recorded the surface temperature of the CPU, as well as the thermal conductivity of the nanofluids, and finally the flow resistance. The results show that the CPU surface temperature was lowered as the mass percentages of the nanoparticles was increased, with the lowest CPU temperature resulting with 0.5% Cu-water, taking the temperature from 49 degrees with deionized water to 34 degrees with 0.5% Cu. This indicates that the nanofluids

	did provide a performance improvement over pure deionized water that is often used for cooling in liquid cooling solutions and that was here used as a baseline. However, another factor was the flow resistance rates. The results show that the higher the mass fraction the higher the flow resistance and the higher the viscosity of the liquid. This means that while the cooling performance of high mass percentages may be better, the nanofluid is hard to move around the cooling loop. From here the conclusion can be made that the best performance can be achieved with a low mass percentage Cu-water solution as this combines high performance with a low viscosity. This can be applied in the future and use int he palace of distilled water in cooling loops in both industrial and small scale personal use settings.
Research Question/Problem/ Need	Does the use of nanofluids in computer cooling solutions involving a radiator and a liquid pump improve the system's cooling performance?
Important Figures	1. Total system diagram:  2. Heat sink:



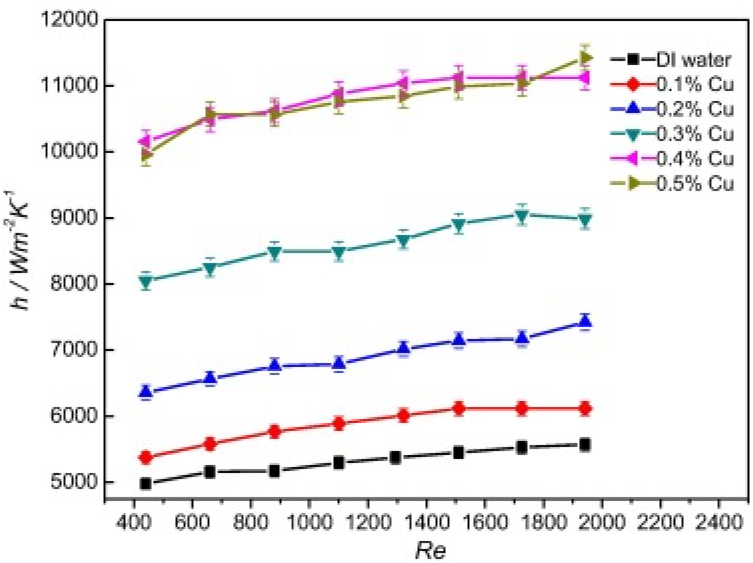
4. The results of the two nanofluids with CPU surface temperature:

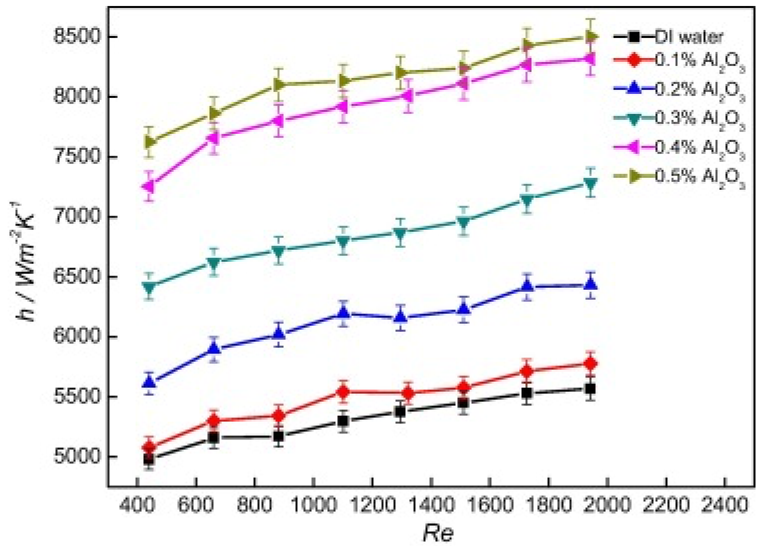




5.

6. The heat transfer coefficient of each nanofluid:

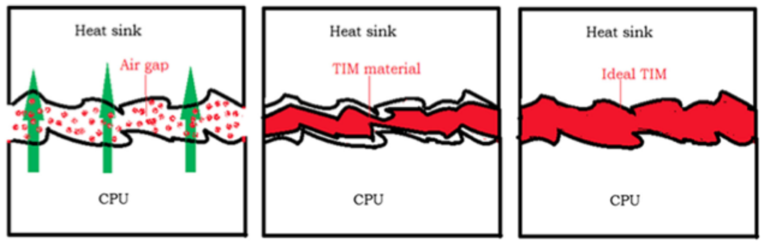


	
Notes	● For this project Cu-water nanofluid as well as Al_2O_3-water nanofluid was used with mass fractions of 0.1-0.5% ● The Reynold's number range was 200-4000 ● When the nano-particles were added the CPU temperature went down a maximum of 18°C ● From 70-80°C every degree increase in temperature can drop longevity by up to 5% in CPU's ● This article focuses on the working fluid for cooling in order to increase thermal performance ● If nanoparticles are added to a fluid that have high thermal conductance they increase the thermal conductivity of the fluid itself ● Using a nanofluid in microchannels in computer silicon greatly increases cooling potential ● A design that used a heater to simulate a CPU, an endothermic work fluid cooler, a copper microchannel heat sink, and a pump was used ● Four thermocouples were placed on the heater and also onto the copper wall of the cooler ● There were also thermocouples to determine the temperature of the fluid going in and out ● Deionized water was the dispersion medium, sodium dodecyl benzene sulfonate was the dispersant, and Cu and Al_2O_3 were dispersed ● The stability of the dispersion was tested, and the results came back good and showed no aggregation or settling ● The more nanoparticles are in a liquid the more viscous it gets and the harder it is to make it flow, thus it counteracts the decreasing thermal resistance that is created by adding nanoparticles

	• The results show that each of the nanofluids had lower CPU surface temperatures with the increase in mass distribution, with 0.4% being close to 0.5% • Cu seems to have performed slightly better • For mass percentages of 0.1-0.2% for the nanoparticles the flow resistance is roughly the same as the deionized water • The increase in the mass percentage results in an increase of the coefficient of performance, but as more nanoparticles are introduced this growth becomes more and more gradual • Cu water can provide up to 2 times the thermal transfer rate, while the Al_2O_3 can provide up to 1.6 times the rate • The higher the amount of nanoparticles the higher the flow resistance • Based off of these two results, the optimum setup would be a low mass percentage of Cu nanoparticles
Cited references to follow up on	1. Z.Y. Guo Frontier of heat transfer-microscale heat transfer Adv. Mech. (1) (2000), pp. 1-6 2. S.U.S. Choi, J.A. Eastman Enhancing thermal conductivity of fluid with nanoparticles ASME. FED, 231 (1) (1995), pp. 99-105
Follow up Questions	1. Would this nanofluid solution eventually settle? 2. Is this nanofluid expensive to manufacture? 3. Would this cause damage to the pump using this nanofluid? 4. Would this nanofluid cause corrosion to the copper block in the cooler?

Article #15: A Review of the Performance and Characterization of Conventional and Promising Thermal Interface Materials for Electronic Package Applications

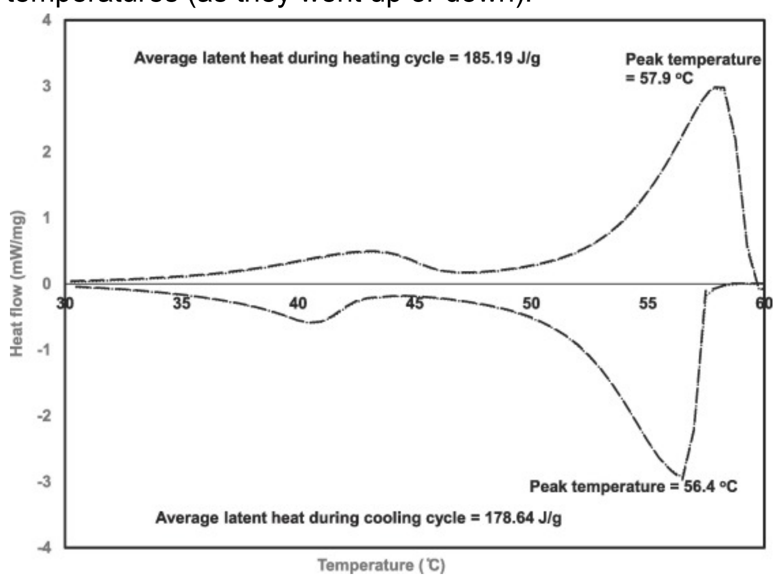
Source Title	A Review of the Performance and Characterization of Conventional and Promising Thermal Interface Materials for Electronic Package Applications
Source citation (APA Format)	Swamy, M. C. K., & Satyanarayan. (2019). A review of the performance and characterization of conventional and promising thermal interface materials for electronic package applications. Journal of Electronic Materials, 48(12), 7623-7634. http://dx.doi.org/10.1007/s11664-019-07623-7.
Original URL	https://www.proquest.com/docview/2292434256?pq-origsite=primo&accountid=29120
Source type	Review Article
Keywords	1. Thermal interface material: a material that decreases thermal resistance between a solid and a solid object 2. Low-melting alloy (LMA): An alloy that is made to be easily fused or melted at relatively low temperatures 3. Carbon-nanotube: Extremely small tubes made out of carbon with diameters around the size of one nanometer and as such have special abilities 4. Grease pump-out: When grease forms a cap by solidifying on top of, in this case, thermal grease
Summary of key points (include methodology)	In this article the goal was to review previous and potential future thermal interface materials (TIMs) and their abilities of cooling electronic integrated circuits. First, it was discussed that TIMs are needed in order to improve the cooling performance and to reduce the thermal resistance between heatsinks and the heat spreader in CPUs. There are multiple types of TIMs. The first of which and the most used is thermal paste/grease, which consist of a silicon grease or oil filled with thermally conductive particles. However, it has drawbacks as it can often dry out or the parts can separate. HOwever, adhesives such as epoxy and films can be used to achieve almost the same thermal performance without these drawbacks, but the performance is often not any better and they can

	be harder to install and produce. Finally, LMA (low melting alloys) exist and are very thermally conductive and have low resistance, however they are oftentimes corrosive and easily oxidate. Additionally, carbon nanotubes and other nanomaterials can be used but they are not currently fully developed. As such the conclusion is that the current solution is oftentimes inadequate, and more development must be done.
Research Question/Problem/ Need	What improvements have been made to thermal grease/paste and what potential innovations can be made?
Important Figures	- A diagram of the levels of “perfectness” for a TIM:  -
Notes	● In order for a computer chip to be adequately cooled it must have both a heat drawing solution such as a heatsink, and a thermal interface material (TIM) to connect the two ● Thermal interface materials can be used to fill the microscopic gaps between two surfaces and to reduce the amount of air bubbles ● Types of TIM’s include pressure sensitive tapes, adhesives, greases, gels, pastes, liquids, pads, PCMs, graphites, and solder ● Good TIM’s operate on a continuous basis for thousands of cycles without losing performance ● The most common TIM is thermal paste, which is silicon or oil mixed with conductive materials, usually a metal, carbon based material, or ceramic. Greases have a thermal resistance from 0.1 cm^{2}°C/W-0.55 cm^{2}°C/W. Drawback of thermal grease are grease pump-out and dry-out ● Gels are another TIM, they are more high performance than greases and are also less prone to dry-out and more thermally stable. Typical greases have a thermal resistance of around 0.3 cm^{2}°C ● Thermal pads consist of a silicon or other elastomer pad filled with ceramic conductive material, and can sometimes shave film or fiberglass reinforcement, and they do not often dry out. They usually have a thermal resistance of 1-3 cm^{2}°C. Over time the pads can be squished and have higher thermal

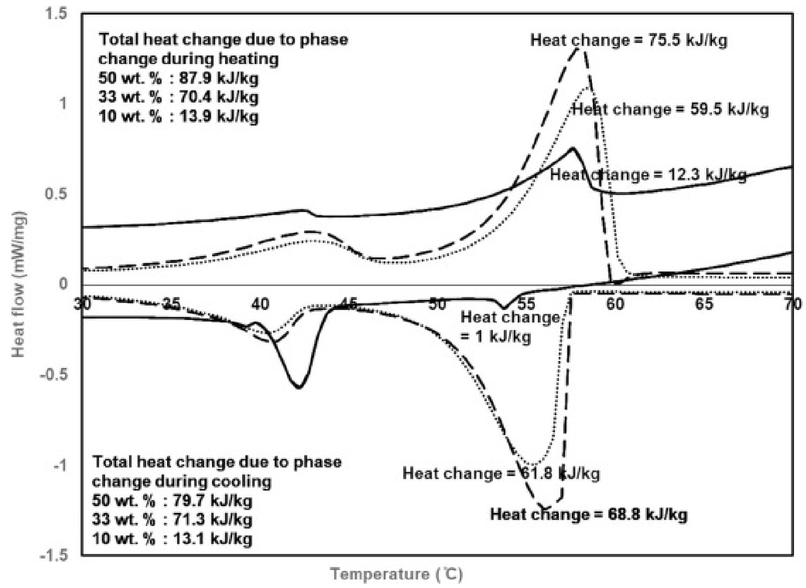
	resistance ● Low melting alloys usually consist of multiple metals that melt at a temperature at or around the operating temperature of CPUs, and they can consist of many metals. They are able to effectively fill gaps when they melt, and do not dry out. They are usually able to have a thermal resistance of around 0.05 cm^2°C, however they can cause corrosion and oxidation which reduces their performance ● Carbon nanotubes can be used as a standalone cooling solution or a composite with graphene, but has to be produced at temperature of above 600°C, but can have thermal resistance rates from 0.01-0.19cm^2°C ● There are many methods for measuring the performance of a TIM, from measuring how quickly temperature changes, to using hot disks, etc., but they each have drawbacks ● PCMs, grease, and gel exhibited high performance but not high performance but all had the drawback of pump-out ● Pads and adhesives do not have this problem, but do not perform better ● However, LMAs do perform much better, but they are corrosive and oxidative ● The conclusion was that the best TIM currently was a elastomer silicone adhesive pad
Cited references to follow up on	None
Follow up Questions	1. Could diamond be used in a TIM? 2. Were thermal greases the first to be invented? 3. Could the gaps in the metal be smoothed instead of the TIMs being required? 4. Would it make more sense to change the performance of TIMs or heat sinks?

Article #16: Paraffin wax–water nanoemulsion: A superior thermal energy storage medium providing higher rate of thermal energy storage per unit heat exchanger volume than water and paraffin wax

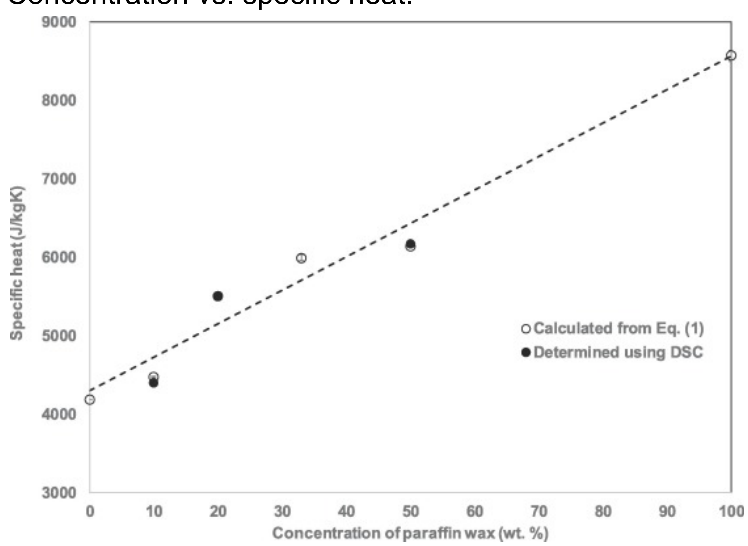
Source Title	Paraffin wax–water nanoemulsion: A superior thermal energy storage medium providing higher rate of thermal energy storage per unit heat exchanger volume than water and paraffin wax
Source citation (APA Format)	Sivapalan, B., Neelesh Chandran, M., Manikandan, S., Saranprabhu, M. K., Pavithra, S., & Rajan, K. S. (2018). Paraffin wax–water nanoemulsion: A superior thermal energy storage medium providing higher rate of thermal energy storage per unit heat exchanger volume than water and paraffin wax. Energy Conversion and Management, 162, 109–117. https://doi.org/10.1016/j.enconman.2018.01.073
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0196890418300864
Source type	Journal Article
Keywords	1. Nanoemulsion: A suspension of particles smaller than one nanometer in another liquid 2. Rate of storage per unit volume: How quickly energy can be stored in a substance per unit amount of volume, usually measured in W/m^3 3. Heat exchanger volume: The amount of a material that aids in heat exchange 4. Microencapsulation: When very small particles are put into other particles so that they can be removed with force
Summary of key points (include methodology)	In this experiment the authors realized that there is no real emulsion fluid that can be used for thermal energy storage. The reason is that already existing phase change material energy storage systems or latent heat storage systems have either a low energy density or a low thermal conductivity. Thus, a combination of both a working fluid and emulsified phase change material particles was used. Multiple tests were conducted, but the emulsified liquid itself consisted of water, paraffin wax particulates, and a surfactant (to stop the particles from coagulating as they are hydrophobic). The solution was then tested in multiple situations, the chief with different concentrations of wax, at

<table>
<tr><td></td><td>10, 20, 33, and 50% concentrations. All of these resulted in higher specific heat capacities than water and higher thermal constance rates than paraffin wax. Thus it was a convenient middle ground. For the results a new measurement was used, energy stored per unit time per unit volume. The results show that this was highest at the 10% concentration, and thus this is the ideal solution. The reason for this is due to multiple factors, from viscosity to thermal conductivity. This provides applications for use as a energy storage medium that is closer to perfect, with both a high energy density and high heat conductivity.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>What is the ideal concentration of paraffin wax in a paraffin wax-water emulsion for it to be most effective as heat energy storage material?</td></tr>
<tr><td>Important Figures</td><td>1. This figure shows the release and absorption (melting) of heat during the heating and cooling periods at different temperatures (as they went up or down):


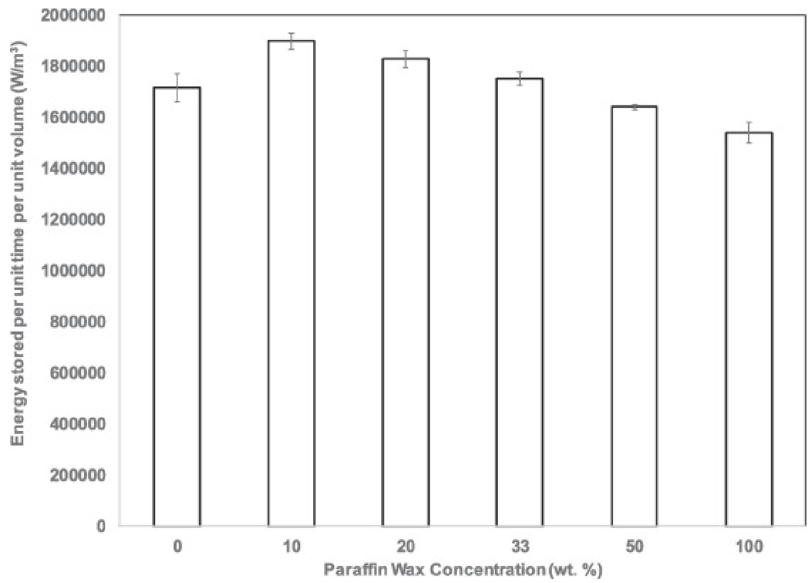
2. Heat change during phase change:</td></tr>
</table>



3. Concentration vs. specific heat:



4. Energy stored per unit time per unit volume at all concentrations:

	
Notes	● Many existing thermal energy storage solutions have problems. Phase change materials have low thermal conductivities and there are efforts to improve this with finned heat exchangers, metal foams, etc. ● Water can be an alternative to PCM's as it has a higher heat capacity than other coolants and a quick charge/discharge rate ● PCM's can be immersed in a liquid to form a phase change emulsion, and the dispersion of organic PCM's in water has been extensively tested ● PCM's can even be encapsulated and then dispersed ● When the PCM's are dispersed they increase the specific heat of the conductance by later amounts, in once case by 200% ● Some of the drawbacks are that PCM emulsions have high viscosities, are thermally unstable, and cannot be supercooled, thus the goal is to have small non-viscous drop sizes ● In this article paraffin wax (PCM) is dispersed in water, so you get a low viscosity liquid with a higher thermal conductance and specific heat capacity ● This paraffin wax melted at 58-60 degrees Celsius ● The emulsion was made by melting the wax and dripping it into the water which was being stirred and radiated by ultrasound ● A surfactant (something which reduces surface tensions) had to be used as the paraffin wax was hydrophobic ● The emulsion was looked at before and after a heat cycle, where it was heated for 30 seconds and then measured for 1 minute

	• The melting temperature of the paraffin wax in the emulsion was also measured • Because the paraffin particles were so small their thermal resistance was negligible • When scanned before and after three heating cycles the size of the particles did not change, which shows that the surfactant worked against aggregation • The majority of the wax melting occurred at 57.9 degrees Celsius and most of it froze at 56.4 degrees Celsius • The temperature of melting and freezing is different with different concentrations • As the amount of paraffin wax went up, the specific heat went up • At 50% paraffin wax the specific heat was 47% higher than at 0% • As the amount of paraffin wax went up the specific heat increased, and as the amount of paraffin wax went up the increase in thermal conductance compared to paraffin wax went up, but it provided a lower increase at higher percentages • A PCM with higher conductivity and heat capacity might be better • As the temp went up, the viscosity decreased in the emulsions • Convection increases thermal conductivity • The 10% paraffin wax solution has the highest energy stored per unit time per unit volume
Cited references to follow up on	1. J. Chen, P. Zhang. Preparation and characterization of nano-sized phase change emulsions as thermal energy storage and transport media. *Appl Energy*, 190 (2017), pp. 868-879, 10.1016/j.apenergy.2017.01.012
Follow up Questions	1. What would be an alternative to paraffin wax? 2. Could car coolant be used for the liquid? 3. What would occur at higher movement speeds? 4. What would happen at higher temperatures?

Article #17: Optimizing performance per watt on GPUs in High Performance Computing: temperature, frequency and voltage effects

Source Title	Optimizing performance per watt on GPUs in High Performance Computing: temperature, frequency and voltage effects
Source citation (APA Format)	Price, D. C., Clark, M. A., Barsdell, B. R., Babich, R., & Greenhill, L. J. (2014). Optimizing performance per watt on GPUs in High Performance Computing: temperature, frequency and voltage effects. *Comput Sci Res Dev*, 31, 185–193 (2016). https://doi.org/10.1007/s00450-015-0300-5.
Original URL	https://arxiv.org/pdf/1407.8116.pdf
Source type	Journal Article
Keywords	1. Performance per watt: how many calculation a computer can do per watt of energy 2. GPU: graphic processing unit, a part of a computer used for doing graphics related calculations 3. HPU: High performance computing 4. DVFS: Dependent voltage and frequency scaling, when voltage and frequency are changed based on the situation 5. Clock speed: how many oscillations of voltage a CPU does per second, measured in Hertz
Summary of key points (include methodology)	The goal of this project was to see whether or not changing the frequency, temperature, and voltage of a computer chip would increase its performance. This was done through the use of a Nvidia K20 GPU which was then liquid cooled. The voltages were then changed and the results were found after stress testing the GPU in different scenarios. The results show that the most optimal performance can be achieved when using a high clock speed, as this increases the amount of calculations that can be done per second. However, there is a limit to this in terms of the semiconductors themselves as well as a thermal limit, as the frequency increases the temperature increases. Additionally, as the voltage decreases the efficiency decreases as the power draw decreases for the same amount of calculations. Thus the best decision is to undervolt and overclock the GPU. However, temperature must also be accounted for as the results show that the energy leaked decreases at lower temperatures, and thus a balance must be maintained. The optimal

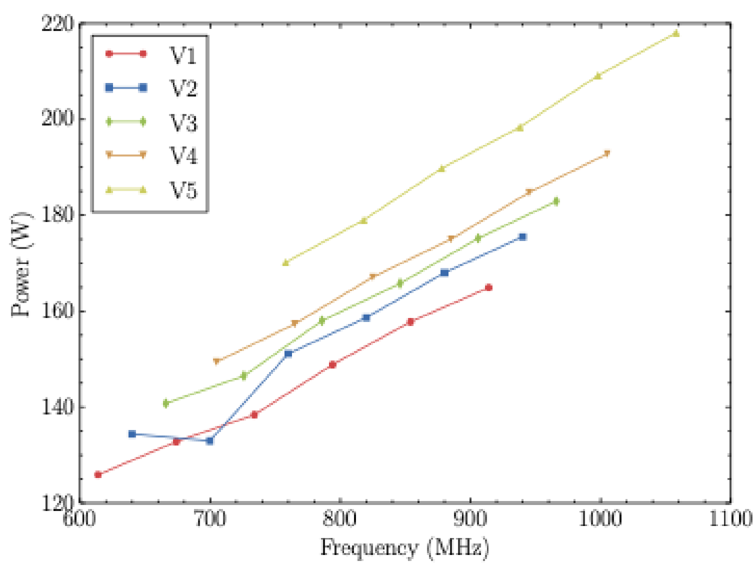
	solution is thus a thermally balanced undervolted and overclocked solution.This is practical in increasing the efficiency of industrial application computing as on large scale energy intensive calculations every little bit of saved electricity helps.
Research Question/Problem/ Need	How can the voltages and clock speeds of a cpu be changed in order to achieve the best performance, temperatures, and energy demands
Important Figures	1. A table of the tested voltages, V1-5: (see table below) 2. Power related to frequency for different voltages: (see chart below) 3. Efficiency at different frequencies:

1. A table of the tested voltages, V1-5:

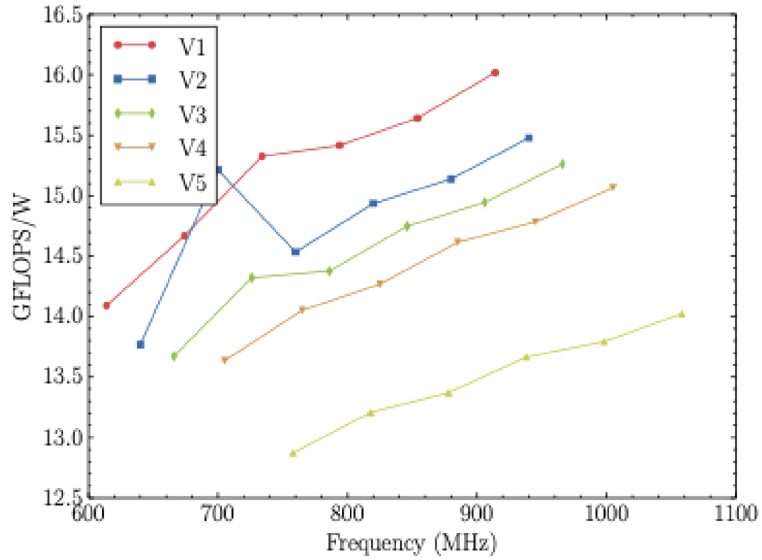
GDDR5 Freq. (MHz)	Core Freq. (MHz)	State ID	GPU Core Voltage (mV)
2600	758	V5	987.5-1112.5
	705	V4*	950-1062.5
	666	V3	925-1050
	640	V2	912.5-1025
	614	V1	900-1000
324	324	V0	875 - 875

*Default value

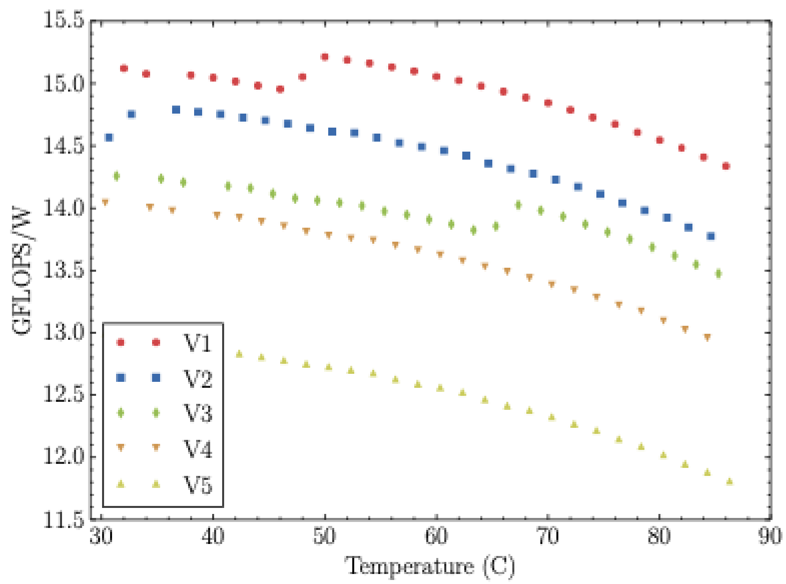
2. Power related to frequency for different voltages:



3. Efficiency at different frequencies:



4. Efficiency related to temperature at differenct frequencies and voltages:



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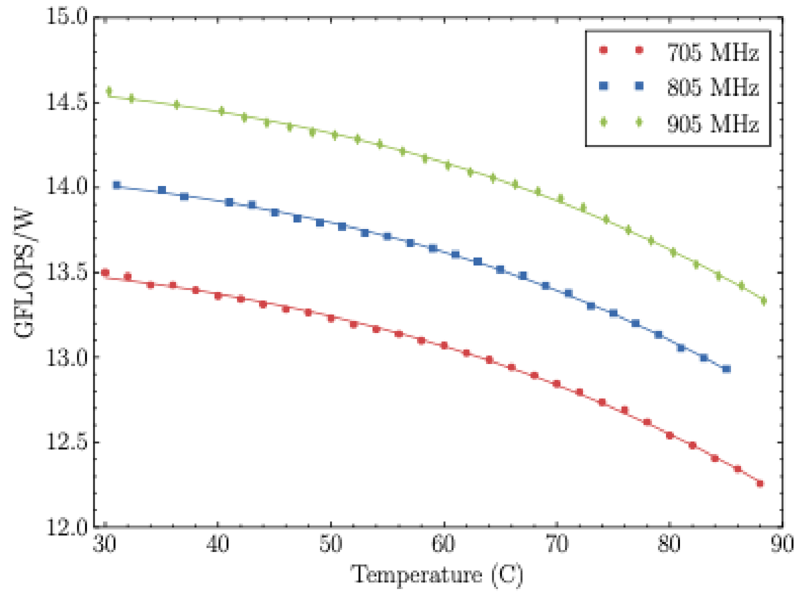
<tr><td></td><td>
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<tr><td>Notes</td><td>

- Here the performance per watt of GPU's is investigated based on temperature, core clock frequency and voltage
- GPU power consumption increased quadratically with increases in voltage and temperature
- An Nvidia K20 GPU was used
- When voltage was decreased and clock speed was increased the temperature remained the same but performance increased by 37-48%
- Reducing the power draw also reduces the temperature, which reduces the cooling power draw, etc, etc.
- The power draw in this case is sued for a radio telescope
- Power efficiency is measured in the amount of calculations that can be done per watt, often called FLOPS/W
- Some energy also leaks
- Transistors become more efficient with lower temperatures
- Usually core clock counts and voltages are changed together, but here they are separate
- The system was water cooled
- Different softwares were used for parameter tweaking
- Given testing at different voltages for the IV being frequency and the DV being power draw and efficiency the lowest voltage or V1 appears to offer the highest efficiency and lowest power draws
- The highest efficiency occurs at the lowest voltage at 914 Mhz with an increase of 18% power efficiency
- The current leak is proportional to temperature
- Power efficiency increases as frequency increases
- The temperature difference led to a 16.7% power draw

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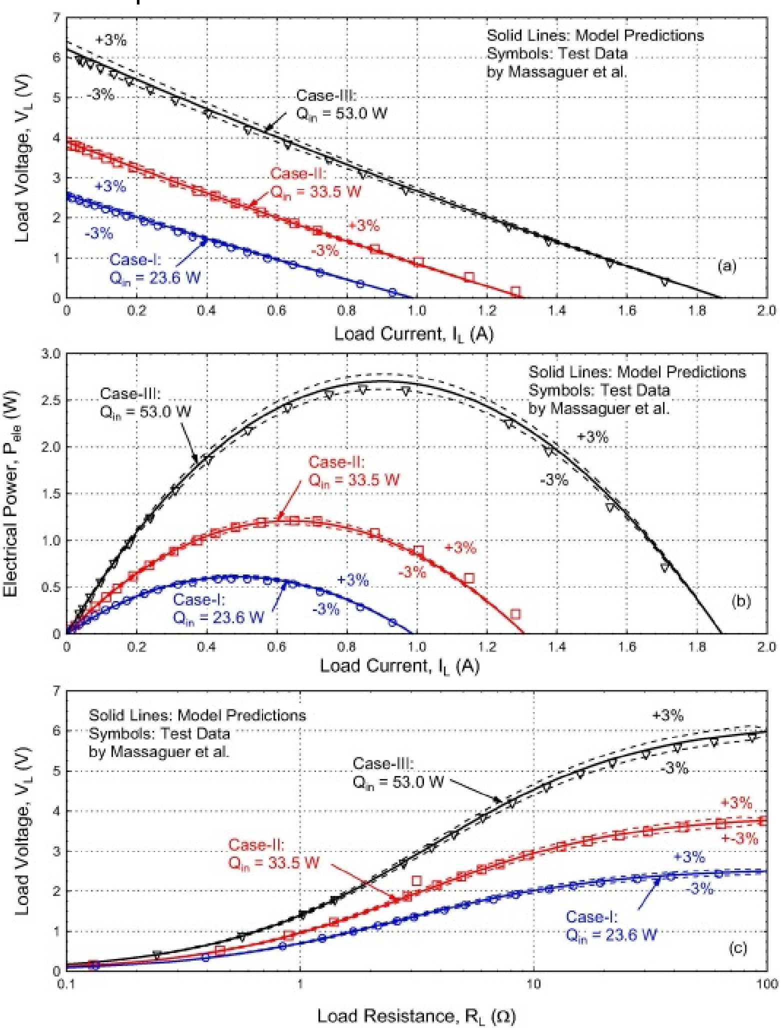
	difference ● The best performance is gotten as a result of undervolting and overclocking the GPU, but overdoing this can result in freezing and crashes, as well as high temperatures if it is too far overlooked ● The efficiency can be increased by up to 48% ● The power draw was decreased from 154 W to 124 W at the same time as performance went from 2064 GFLOPS to 2636 GFLOPS ● A system could be created that would dynamically change these values for optimal operation ● The liquid cooling system was more powerful and sued less electricity than the stock cooling solution, and in the real world liquid cooling can be more than 15% more efficient ● Code is often optimized, but this kind of work can be done as well, keeping temperature in mind as a source of potential energy optimization
Cited references to follow up on	1. Collange, S., Defour, D., Tisserand, A.: Power Consumption of GPUs from a Software Perspec- tive. In: Computational Science–ICCS, pp. 914– 923. Springer, Berlin, Heidelberg (2009)
Follow up Questions	1. Would this create extra chip wear? 2. Why do more systems not include liquid cooling? 3. Could an automatic code be created to find the optimum values? 4. Does undervolting a chip cause long-term failure or unreliability issues?

Article #18: Performance optimization of cascaded and non-cascaded thermoelectric devices for cooling computer chips

Source Title	Performance optimization of cascaded and non-cascaded thermoelectric devices for cooling computer chips
Source citation (APA Format)	Saber, H. H., AlShehri, S. A., & Maref, W. (2019). Performance optimization of cascaded and non-cascaded thermoelectric devices for cooling computer chips. *Energy Conversion and Management*, *191*, 174–192. https://doi.org/10.1016/j.enconman.2019.04.028
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0196890419304406
Source type	Journal Article
Keywords	1. Conversion efficiency: The percentage of energy that is converted from one form into another 2. Self sustainable cooling network: A cooling network that is able to continue running without outside energy inputs 3. Cascading thermoelectric generator: A thermoelectric generator which consists of multiple TEGs/TECs 4. Segmented thermoelectric generator: A generator in which the generating segments are electrically separated 5. Gravity assisted heat pipe: a heat pipe similar to a normal heat pipe used in laptops but one that uses gravity for working liquid movement
Summary of key points (include methodology)	The goal of this article was to first numerically simulate how a self-sustaining cooling network of TEGs that feed a TEC could be created, and then put that into practice. After doing calculations and comparing them to given results the difference was only around 4%, showing that the model that was created was accurate. Then the goal was to find the optimal design, and to do this the cases were run for different values and different designs, and the optimal scenarios were found. In this case the TEGs were placed on areas with low heat flux, adnt he TEC was placed on the area of the CPu with high temperature, also called the hotspot. This allowed for the optimal temperature and electrical production. After this was done the results showed that there can be multiple optimal scenarios, but with 24/25 segments of a CPU continuing TEGs and the last one, the hotspot, having a TEG, the temperature can be decreased by around 6

<table>
<tr><td></td><td>degrees Celsius on the hotspot, adn the average temperature of the chip can also be decreases. However, because the efficiency of conversion for these thermoelectric devices is so low, around 0.6%, it is recommended that in the future the focus is on improving the efficiency of the devices themselves.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>Can thermoelectric generators produce enough power to allow thermo-electric coolers to be used for a self sustaining cooling network?</td></tr>
<tr><td>Important Figures</td><td>

1. Results of predictions:



2. Hotspot setup:

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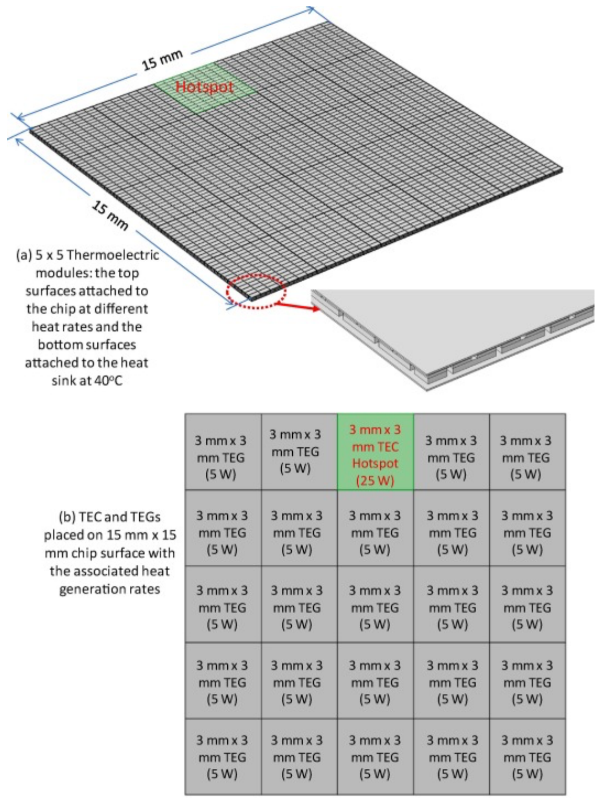
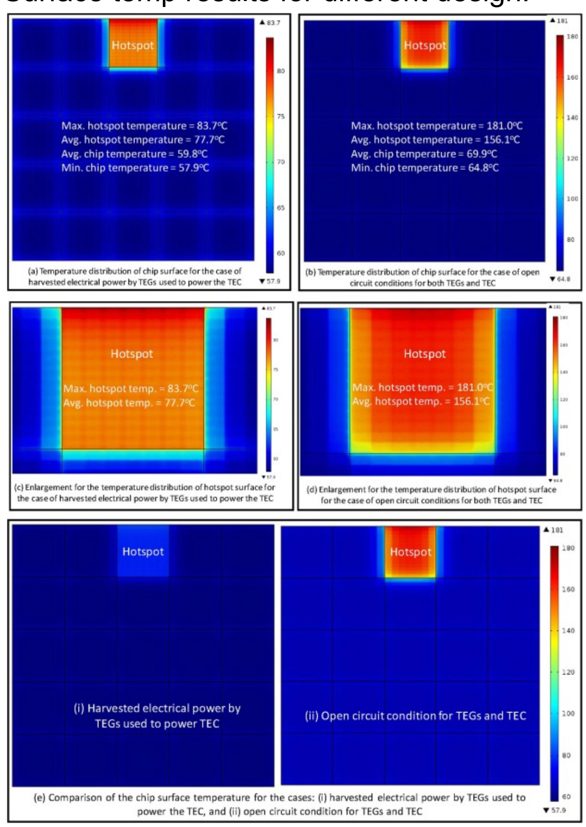


3. Surface temp results for different design:

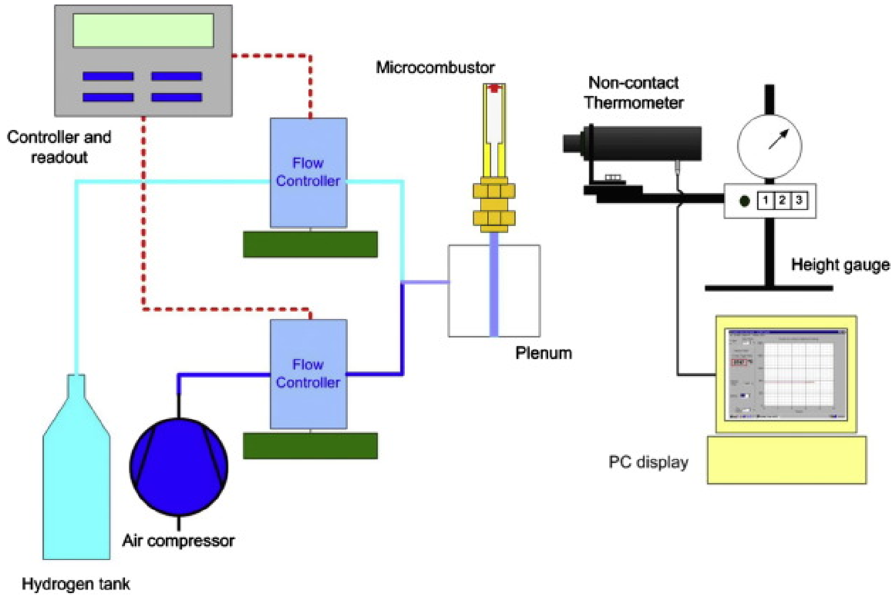


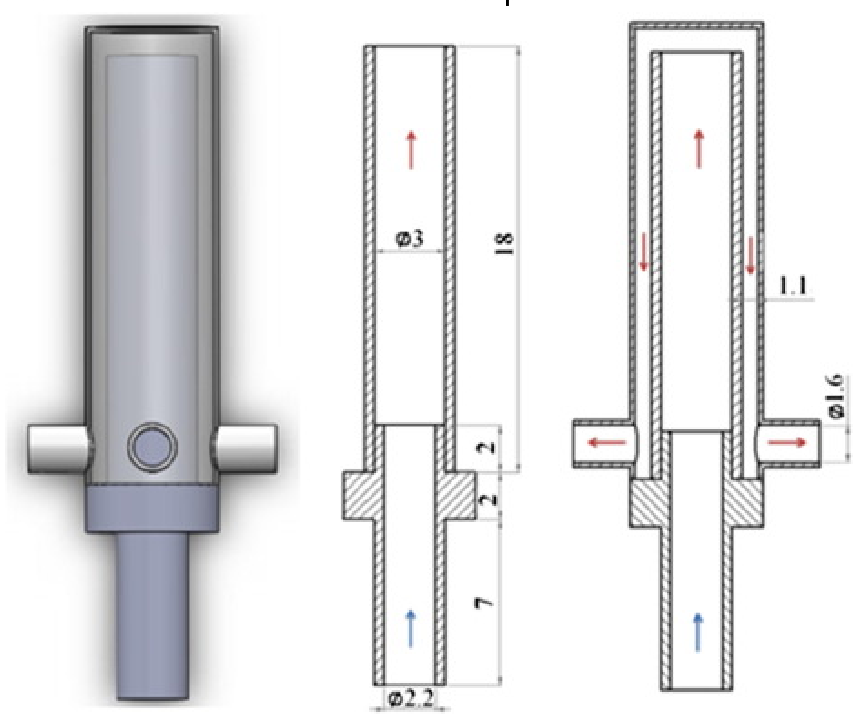
Notes	● They created a sustainable cooling network by connecting the energy created by the thermo-electric generator and using it to power thermo-electric coolers ● The optimization was done through a 3D model and then validated with experimental data, with a +/- 4% agreeance ● They also talk about optimizing cascading and non-cascading thermoelectric coolers and generators ● Scaling down voltage to control temperature can result in worse performance ● By boiling liquids with low melting points the temperature can be reduced ● To reduce the temperature on the hot side of a TEC a heat pipe has been recommended ● Very thin superlatives can be used directly inside of CPU dies, or even embedded TECs ● TEGs can be used to cool, and if they are connected or their efficiency is improved their cooling ability goes up ● For a TEG/TEC to be made two different semiconductors are connected in thermal parallel and in electrical series ● TECs are commonly used in lasers, blood analyzers, etc., while TEGs are used in automobiles, body heat devices, etc., and place where there is waste heat ● TEGs were installed in cooler areas and TECs in hotter areas ● Copper and ceramic were used as insulators ● Multiple TEG/TECs stacked on top of each other were tested, and these are called cascading ● The COP (coefficient of performance) was tested with different design and with and without contact resistances ● This model was compared to Cheng. et al.’s test results using their values, and the model predicted values that were off by +/- 4%, and when compared to another data set the results were within 3% ● While the power production can be increased with cascading TEGs, the temperature of the CPU also increases ● If the devices are subject to higher CPU temperatures, they generate more electricity, but the temperature may overall be higher ● The conversion efficiency for TEGs was 0.6% ● Depending on how TECs are structured, the optimal voltage and amperage necessary can be reduced or changed ● By chang the length of the semiconductor cubes in the TEG/TECs the temperature can be reduced ● Depending on the height of the cubes the optimum temperature of the chips, and depending on whether or not the device is cascaded the optimal temperature and positions change ● It is concluded that the performance of the TEC/TEGs should

	be improved ● Out of 25 segments in the optimal design, one had a TEC and the rest had TEGs ● Using the above one TEC design the temperature of the hotspot was 6 degrees Celsius lower
Cited references to follow up on	1. T. Carlson, T. Heirman, L. Eeckhout. Sniper: exploring the level of abstraction for scalable and accurate parallel multi-core simulation number 52. Conference on High Performance Computing Networking, Storage and Analysis (Supercomputing – SC) (2011) Google Scholar
Follow up Questions	1. Why was there only one hotspot? 2. How can the performance of thermoelectric devices be improved? 3. Is there a limit to the performance of thermoelectric devices? 4. Would this system be expensive to produce?

Article #19: Development of micro-thermophotovoltaic power generator with heat recuperation

Source Title	Development of micro-thermophotovoltaic power generator with heat recuperation
Source citation (APA Format)	Yang, W. M., Chua, K. J., Pan, J. F., Jiang, D. Y., & An, H. (2013). Development of micro-thermophotovoltaic power generator with heat recuperation. *Energy Conversion and Management*, *78*, 81–87. https://doi.org/10.1016/j.enconman.2013.10.040.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0196890413006754
Source type	Journal Article
Keywords	1. Heat recuperator: A device that recovers heat that would otherwise be lost 2. Micro-thermophotovoltaic power generator (MTPVG): a very small power generator that turns infrared radiation or heat into electricity 3. Micro combustor: A combusting device that operates and the micro level 4. Micro fabrication: The process of creating devices that are on the micrometer scale of size
Summary of key points (include methodology)	The goal of this experiment was to model a design that would predict accurately given the fuel flow rates, the air to fuel ratio, and the design of a combustor the energy production and temperature of the system. After this was modeled the results were very close to the expected values, so they were checked with an experimental model. A combustor that consisted of a hydrogen fuel consuming device that was constructed out of a quartz glass tube, that would consume and combust the hydrogen and oxygen, with and without a heat recuperator. The device was then tested at several different fuel flow rates and oxygen to fuel ratios. The results show that a heat recuperator can significantly increase the temperature of the walls, as well as significantly decrease the temperature distribution difference. This improves the performance of the photovoltaic cells as well by increasing the photon flow as well as “tuning” the right photon frequency. The use of a heat recuperator increased the wattage output by up to 70%.

<table>
<tr><td>Research Question/Problem/ Need</td><td>How does using a heat recuperator affect the energy output of a micro combustion powered thermophotovoltaic power generator?</td></tr>
<tr><td>Important Figures</td><td>The experimental design:


The combustor with and without a recuperator:


The PVC design:</td></tr>
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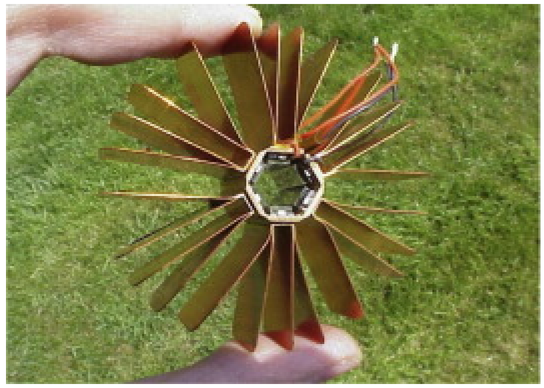
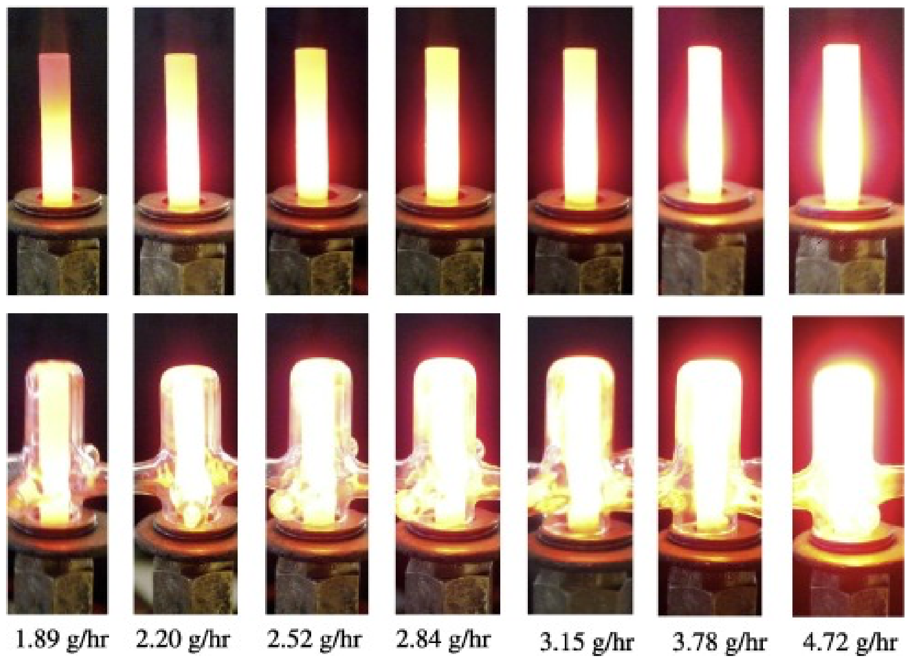
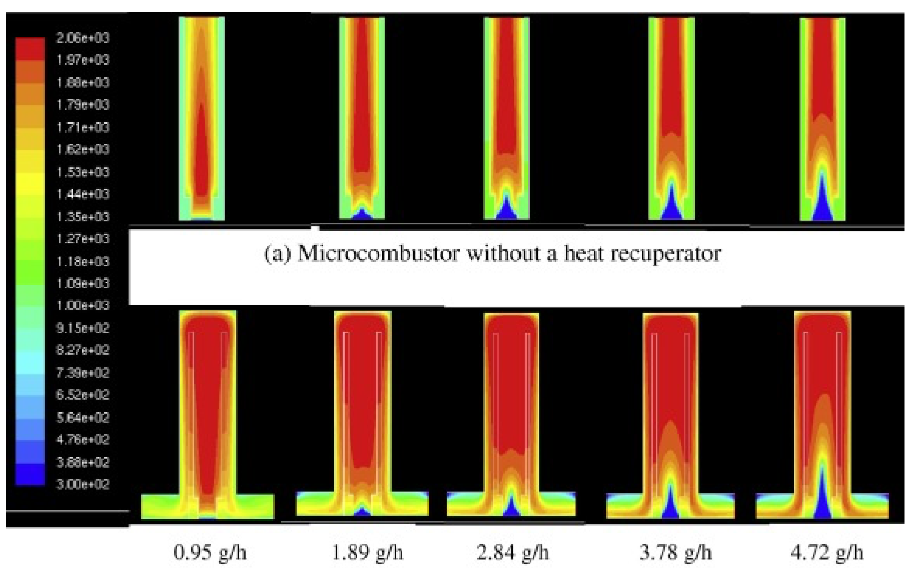


The combustion without (top) and with (bottom) a heat recuperator:

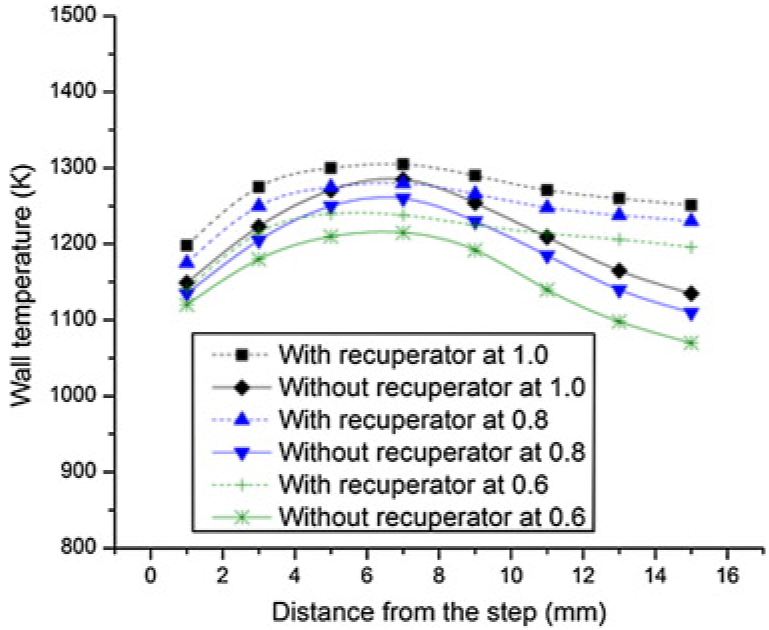




(a) Microcombustor without a heat recuperator

(b) Microcombustor with a heat recuperator

<table>
<tr><td></td><td>All results compared:



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<tr><td>Notes</td><td>

As more and more microelectronic devices have been made, the demand for energy sources for these has increased, and as batteries have low energy densities and are overall not that good for this application, micro combustion has been used
TPV generators are capable of producing electricity in a noiseless way, with a heat source that emits photons when hot enough, and then generates electricity using narrow wave-range photovoltaics
Oftentimes the heat source is the emitter, but sometimes it is not, however combustion can be used as both a heat source and an emitter
They modeled the results first using mathematical equations and assumptions
They used hydrogen as their heat source and combustion gas
For the experimental data they used a micro combustor, as well as some flow gauges, an IR thermometer, a PC, and some tubes
A design was made with an without a recuperator, and the tube was made of quartz to allow for photon transfer
For the photovoltaic cells multiple layers of ranged photovoltaics were used and were cooled by a finned copper heatsink
The heat recuperator allowed for higher temperatures and for lower temperature gradients
In one case, the heat recuperator allowed for a 100 K

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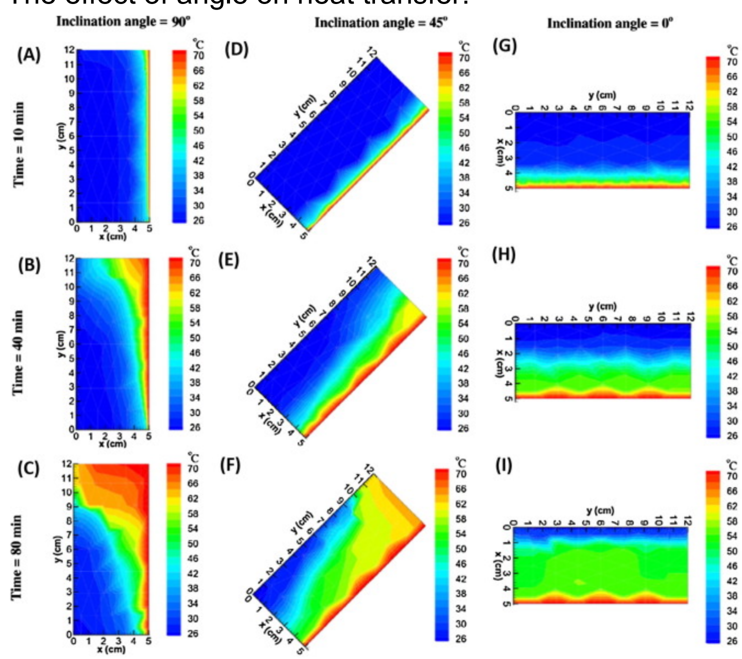
	temperature increase ● The heat different went down from 200-130 degrees Kelvin with the heat recuperator, and the wattage was increased by 35% ● The higher the fuel rate the higher the temperatures ● When a heat recuperator was used the highest wattage gain was 70%, as the photon range was also much more useful
Cited references to follow up on	1. A.F.P. Carlos Micropower generation using combustion: issues and approaches Proc Combust Inst, 29 (2002), pp. 883-899 Google Scholar 2. M. Madou Fundamentals of microfabrication (2nd ed.), CRC Press, Boca Raton (2002) Google Scholar
Follow up Questions	1. Would there be a better alternative to quart walls? 2. Could the photons be converted into the right range? 3. What other TPV systems exist? 4. Would this provide any benefit over already existing solar panels?

Article #20: A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility

Source Title	A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility
Source citation (APA Format)	Khan, Z., Khan, Z., & Ghafoor, A. (2016). A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility. *Energy Conversion and Management*, *115*, 132–158. https://doi.org/10.1016/j.enconman.2016.02.045.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0196890416300759
Source type	Review Article
Keywords	1. Enthalpy: Heat content of a system 2. Supercooling: When something goes below its melting point without freezing 3. LHS : Latent heat storage 4. Encapsulation: the process of covering a certain substance with another, for the purpose of physically isolating it from its environment
Summary of key points (include methodology)	The purpose of this article was to review what information exists about latent heat storage (LHS) systems that utilize PCMs (phase change materials) as their primary energy storage material. The research indicates that there are multiple areas which must be assessed to conclude whether or not a certain PCM is viable. One of these is the energy density of the PCM, as well as other factors such as enthalpy, heat of fusion, and cycle count. In order for a phase change material to be useful it must be able to be cycled many thousands of times without considerable loss in performance, as well as being able to absorb large amounts of energy every time, so a higher energy density is also needed. The two main categories of PCMs that fit these necessities are paraffin waxes and salt hydrates. However, each of these are incompatible with a certain type of

	container, as waxes interfere with plastic compositions and salt hydrates are corrosive to metals. Additionally, it was found that the container that they are in also has a significant impact on their performance. If the container is rotated, or the shape or material is changed, this can significantly affect the performance. Additionally, metal meshes or inner tubes can be added to increase thermal conductivity. Next, it was discussed that additives can be included in the PCMs, such as metal meshes, nanoparticles, or the PCMs themselves can be nanoencapsulated. This results in higher performance as well. All of this together paints a picture of multiple factors which can be optimized for optimum performance.
Research Question/Problem/ Need	What techniques and conditions allow each phase change material to best or worse suit a latent heat storage system?
Important Figures	1. The effect of angle on heat transfer:  2. The melting process and convection/conduction:

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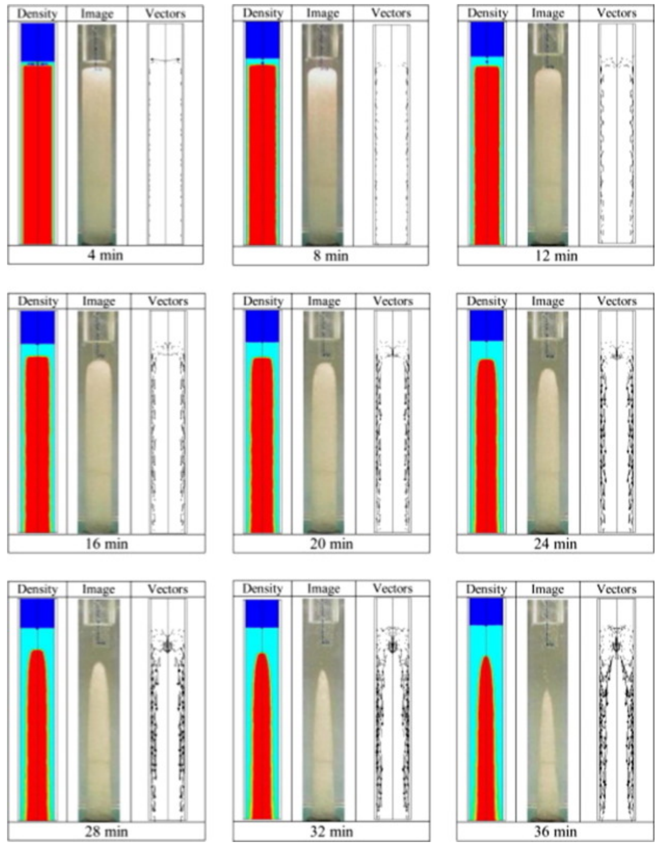
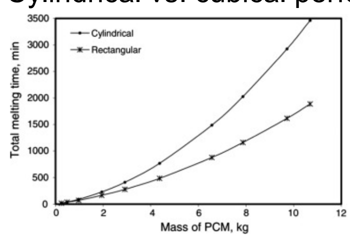
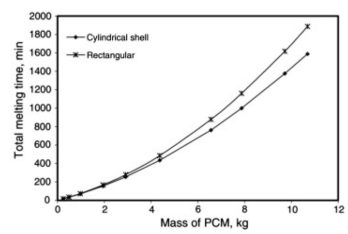


3. Cylindrical vs. cubical performance:





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<td>Notes</td>
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- Use during peak demand hours, store during off hours
- Sensible heat storage systems take much more material to store the same amount of energy as in a latent heat energy storage systems
- PCMs can be encapsulated, or made of metal nanoparticles to increase their stability, energy density, and conductivity
- Two main groups of PCMs are paraffin waxes and salt hydrates, as they are cheap, have a high enthalpy, specific melting point, and are abundant
- One problem with PCMs is that they often have low conductivity
- Paraffin materials have good energy density of, 60–269 kJ/kg and ≅150 MJ/m3, but they have a low thermal conductivity of around ≅0.2 W/m K

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	● Paraffin materials are non-toxic ● Salt hydrates are the most studied PCM type, as they have a high heat of fusion (86–328 kJ/kg and ≅350 MJ/m3), and a higher thermal conductivity than paraffins (≅0.7 W/m K) ● Salt hydrates have a tendency to supercool, and are often corrosive, even to metal ● Paraffin waxes can withstand up to 3000 cycles, but this is dependant on the temperatures that they are subjected to, as the temperature they are subjected to goes up, they have a lower and lower cycle count, and their heat capacity becomes decreased ● Salt hydrates have lower maximum cycle counts of around 1000, as they are corrosive and react, as well as separating into the salt and hydrate molecules ● Aluminum is very salt-hydrate corrosion resistant, and steel is also, albeit less, resistant ● Depending on the angle the amount of heat transferred can be increased, as well as the evenness ● Container shapes that are usually used are cubes and cylinders ● When a PCM first melts usually the heat is transferred by conduction, and then as more beings to melt convection becomes more important ● Adding tubes into the container can improve performance ● Cylindrical containers perform better than rectangular containers of the same volume ● Orientation does not affect solidification for paraffins ● Fins can greatly enhance the performance and greatly reduce the charging time ● If matrices are introduces to the PCM it can improve the performance of the PCM ● Graphite can also increase performance greatly ● Metal nanoparticles can improve performance by almost double ● Multiple PCMs used together can be used to reduce phase transition time ● When 3 waxes are used the phase transition time is decreased by up to 15%, and the transitions all start at the same time ● Encapsulation can result in higher conductivity and higher cycle counts ● With paraffin waxes it can increase the cycle count ● Cylindrical containers appear to be the best
Cited references to follow up on	1. M. Kenisarin, K. Mahkamov. Passive thermal control in residential buildings using phase change materials. Renew Sustain Energy Rev, 55 (2016), pp. 371-398.

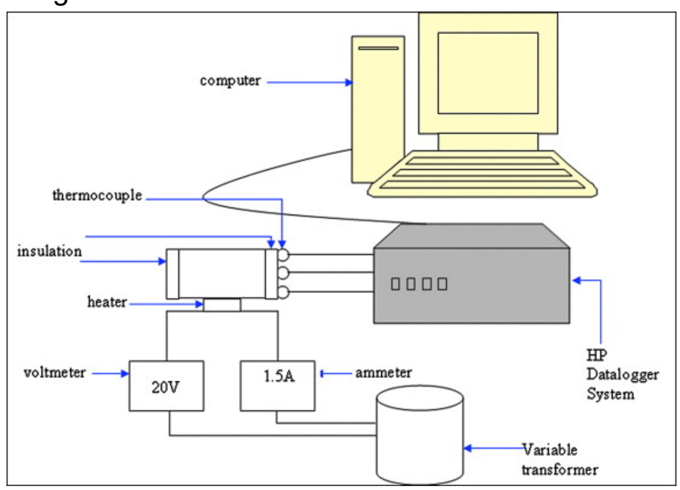
	Article Download, PDF, View Record in Scopus Google Scholar
Follow up Questions	1. How does thermochemical energy storage compare to PCMs and LHS? 2. How can surfactants be used to prevent high density additives from sinking? 3. Can nanoparticles be encapsulated along with the PCM particles? 4. How long do other energy storage systems last in terms of cycles?

Article #21: Experimental and numerical studies on performance of PCM-based heat sink with different configurations of internal fins

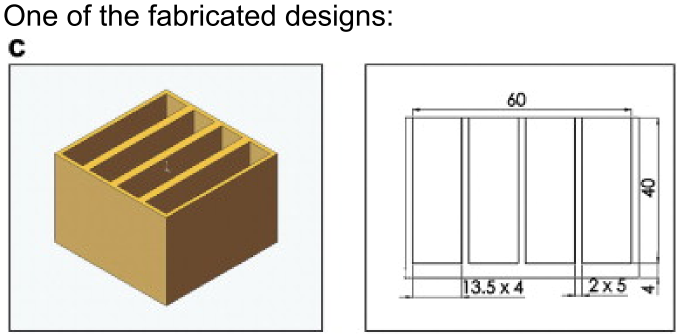
Source Title	Experimental and numerical studies on performance of PCM-based heat sink with different configurations of internal fins
Source citation (APA Format)	Hosseinizadeh, S. F., Tan, F. L., & Moosania, S. M. (2011). Experimental and numerical studies on performance of PCM-based heat sink with different configurations of internal fins. *Applied Thermal Engineering*, *31*(17-18), 3827–3838. https://doi.org/10.1016/j.applthermaleng.2011.07.031.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S1359431111003905#!
Source type	Journal Article
Keywords	1. Thermal conductivity enhancer: A material which increases the thermal conductivity of a material 2. Latent heat of fusion: The amount of change in heat/enthalpy that results from a phase change 3. VOF: Volume of fluid 4. PISO: Pressure-Implicit with Splitting of Operators
Summary of key points (include methodology)	The authors begin by stating why new methods of computer cooling are needed, based on the ever higher heat fluxes. Then they begin to talk about their approach to the problem, which entails a mathematical simulation of an aluminum heatsink that uses a PCM to store energy, and is insulated from the outside environment. The system is then heated up via an electrically powered controlled heat source, and this heat is uniform. This heat source is intended to simulate to some level a computer chip. However, before the authors collected experimental data they compiled a mathematical model of the situation via both a 3D and a 2D method. The results agreed very closely with the experimental data. What was changed in this experiment was the amount of fins, the height of the fins, and the thickness of the fins that were put into the heatsink. The results were gauged in terms of temperature over time. The results show, with a close connection between experimental and theoretical, that increases in find count increase the performance of the system by increasing the time it takes to get to maximum temperature. It also shows that the time that is spent melting decreases as there is less

<table>
<tr><td></td><td>PCM volume. When the fin height was changed the results show that the higher the fins, the better the performance, will all of the same effects as for the amount of fins, such as shorter melting period and delayed melting period. Finally, find width was beneficial when increased, but only marginally and only to a certain point. In this case when the thickness became greater than 4 mm the performance was no longer increased. Of course, the same effects followed. Overall, the results show that increasing find count and height up to 7 and 40mm respectively improve performance greatly, and increasing width up to 4mm increases performance. This can be used as a general concept to use fins to improve PCM heat sink performance in the future.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can fins be used to improve the performance of a phase change material based heatsink?</td></tr>
<tr><td>Important Figures</td><td>

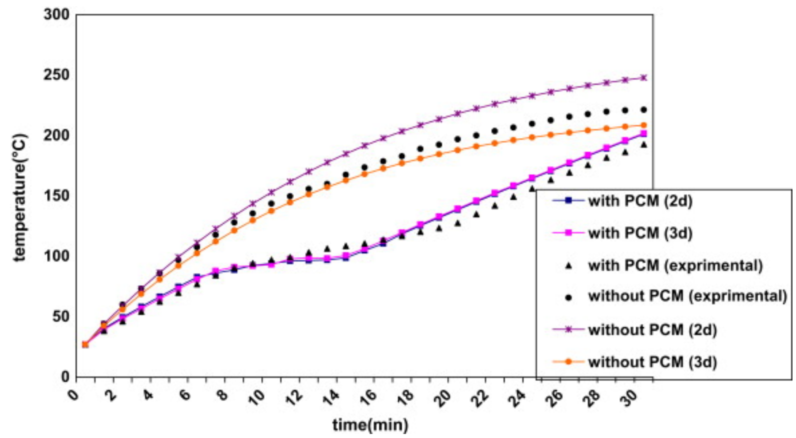
1. Design:



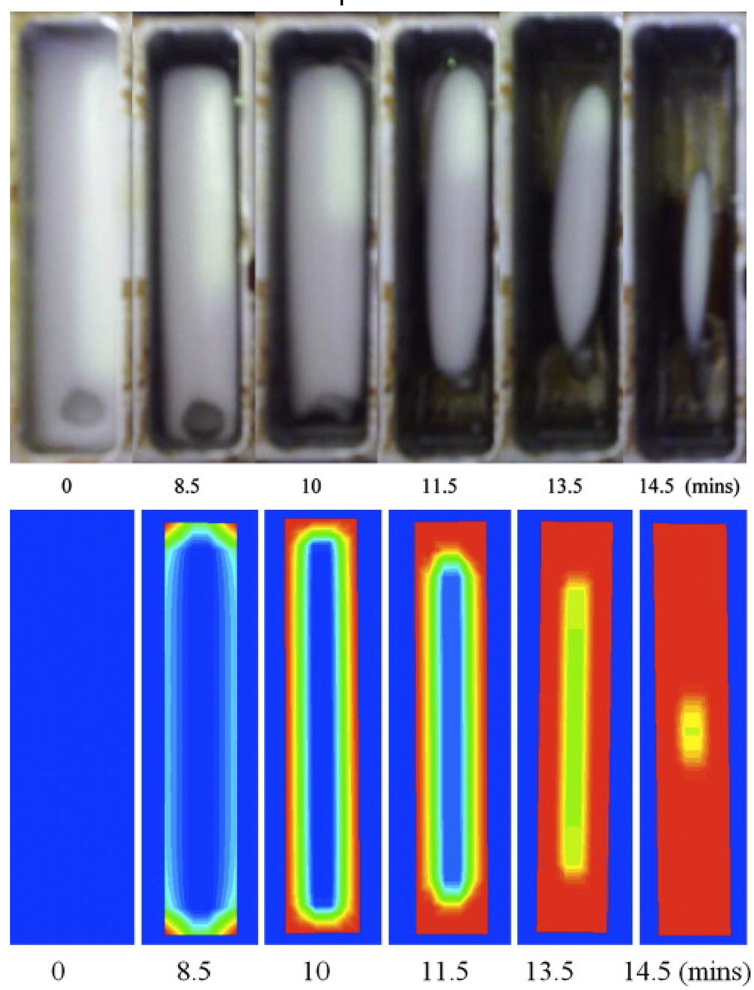
2. One of the fabricated designs:



3. Temp data of all runs experimental and mathematical:
</td></tr>
</table>



4. Actual vs. simulated melt profile:



5. Time to melt at power levels:

<table>
<tr><td></td><td>

Power level(W)	Melting temp (°C)	Duration (mins)
25	80–106	14–32
35	86–106	12–23
45	87–110	7–16

</td></tr>
<tr><td>Notes</td><td>

- One study found that decreasing temperature of a processor by 1℃ will decrease the failure rate by up to 4%
- Passive heatsinks have no moving parts
- An ideal PCM should have a high latent heat of fusion and a small volume changing during phase changes
- Additives can be included into PCMs to make them more conductive
- The parameters of this study are the fin count, fin height, and fin width of the fins included in the container
- The levels of heat sinks are, none, 3, 5, and 9 fins, the height ranged from 10mm, to 20mm, to 40mm, and the thickness went from 2mm, to 4mm, to 6mm
- Int hsi case an artificial heat supply was used, as well as the PCM heat sink being insulated to prevent heat loss, as this can be almost 15%
- For this experiment the heatsink was a box made of aluminum with a thermal conductivity of 180 W/m K
- There were 16 thermocouples to record different temperatures
- The four sides were coated with acrylic and insulating cloth
- A data collection device was used for the temperature data
- They used a ready made PCM, which was melted and then measured out, and then poured, and the PCM was Rubitherm™ RT-80
- Different wattages were supplied to the power supply
- They used a mathematical modeling software called FLUENT to find their mathematical results, and this was a VOF (volume of fluid) model
- Without any PCM in the heatsink the temperature of 100℃ was reached in 5 mins, but with a PCM it took 12 minutes
- Between 10 and 20 minutes the temperature increase is low, and this is where the PCM melts
- The PCM eventually gets to the same temperature as the non-PCM heat sink of 150℃, meaning it needs to be used intermittently and be given time to “discharge’
- The 2D and 3D model agreed closely with PCM data, but only the 2D model matched closely with the non-PCM data
- The expected melt profile matches closely with the actual melt profile

</td></tr>
</table>

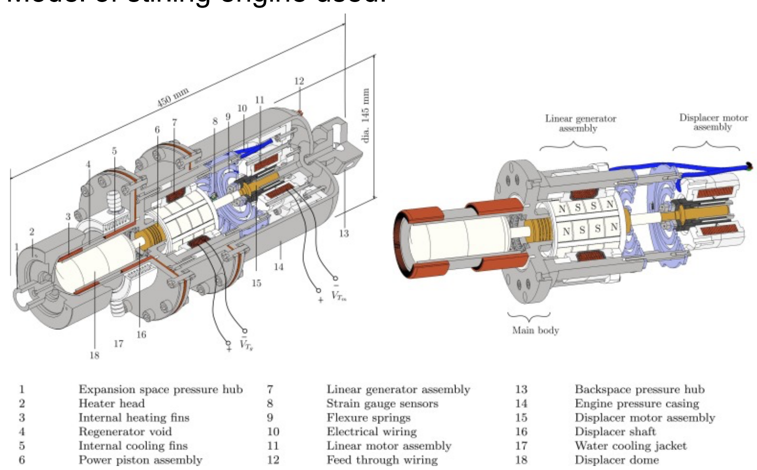
	● The more energy was supplied to the heater the quicker the PCM melted ● The temperature was lower with more fins ● Addings fins increases the thermal distribution evenness ● The more fins the longer it took for melting, as the heat distribution was more even ● More fins meant lower temperature, but higher melting time as there was less PCM ● The optimal thickness was 4mm ● The optimal height was the higher, 10mm, and the higher the fins the more the melting is delayed ● Fins overall improve performance ● Fins create more convection movement
Cited references to follow up on	1. E.M. Alawadhi, C.H. Amon Performance Analysis of An Enhanced PCM Thermal Control Unit, Thermal and Thermomechanical Phenomena in Electronic Systems 2000, Las Vegas, NV, USA, 23–26. (May 2000) Google Scholar
Follow up Questions	1. What occurs when different fins materials are used? 2. Could the fins be made porous? 3. Could something be added to the PCM instead? 4. Could the shape of the container benefit the performance, for example if it was cylindrical?

Article #22: Simulation, manufacture and experimental validation of a novel single-acting free-piston Stirling engine electric generator

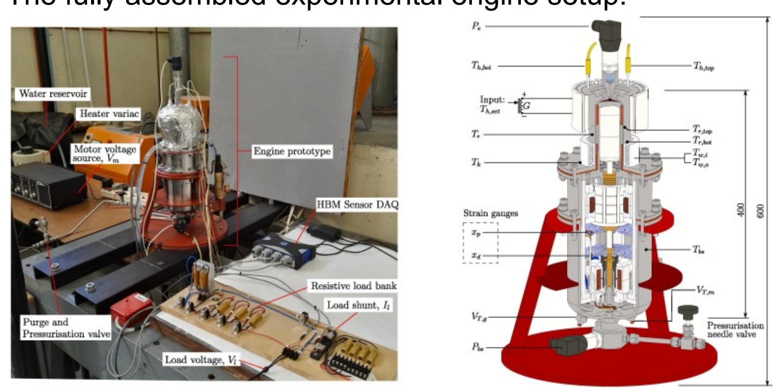
Source Title	*Simulation, manufacture and experimental validation of a novel single-acting free-piston Stirling engine electric generator*
Source citation (APA Format)	de la Bat, B. J. G., Dobson, R. T., Harms, T. M., & Bell, A. J. (2020). Simulation, manufacture and experimental validation of a novel single-acting free-piston Stirling Engine Electric Generator. *Applied Energy*, *263*, 114585. https://doi.org/10.1016/j.apenergy.2020.114585.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0306261920300970
Source type	Journal Article
Keywords	1. Free-piston: Two pistons attached to the same piston rod, without extern attachment, that work together 2. Stirling engine: An external combustion engine that utilizes the expansion of a working fluid to drive the movement of a piston 3. Third-order modelling: The degree to which an equation is written to model something 4. Finite element analysis: Using a mathematical model to predict a specific situation
Summary of key points (include methodology)	The goal of this project was to develop a mathematical model that could accurately emulate all of the aspects of a 100 peak W producing free-piston stirling engine. They then developed a model that simulated mathematically the processes occurring in the gnine using a complex model that leverages the conservation of mass, energy, and other laws to simulate the processes more accurately than is possible with other methods. This results in a complex model that can predict what is occurring at multiple points in the engine. They then also built a physical experimental setup that consisted of the same engine that was modeled, and different resistances to simulate open and closed current flow. In this case they used helium as their working fluid, and they heated up the hot plate to 600 degrees Celsius. They then ran the simulations and compared the results at different points for different measured and compared theoretical results to actual results. This resulted in some

<table>
<tr><td></td><td>discrepancies, particularly in wattage measured. However, the overall results were fairly close. In terms of wattage the simulation overestimated the production by 23.3%, which is likely due to the fact that a lot of extra heat was lost to the engine walls and this was not accounted for in the simulations. Overall, the results were fairly close and the mathematical approach worked well. However, one place that is cause for concern is the efficiency of the gnine, which is around 2.59%, and this is fairly low. This is also likely due to heat loss into the engine walls, but this is a place that future research can focus on.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can a mathematical model best be used to simulate a free-piston based stirling engine generator?</td></tr>
<tr><td>Important Figures</td><td>

1. Model of stirling engine used:

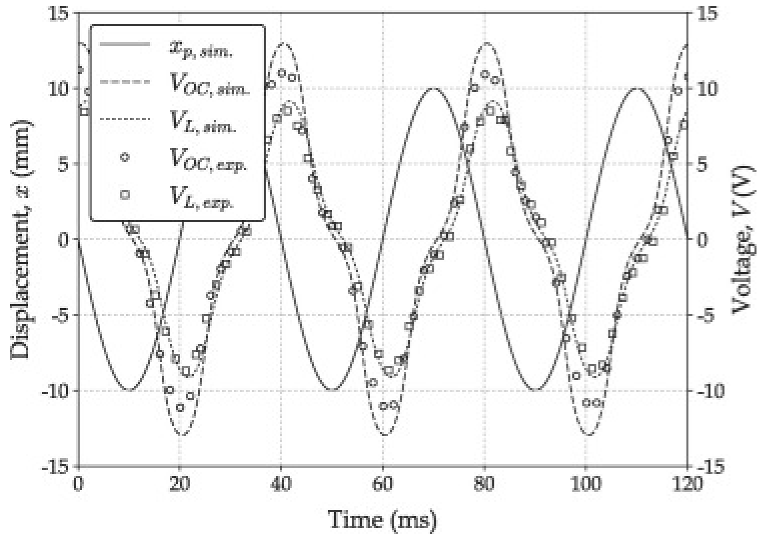
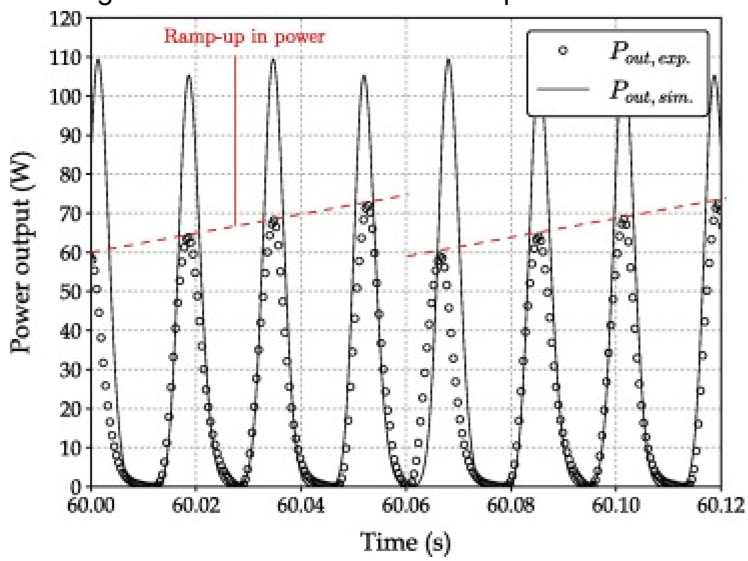


2. The fully assembled experimental engine setup:



3. First set of modeled vs. experimental data:

</td></tr>
</table>

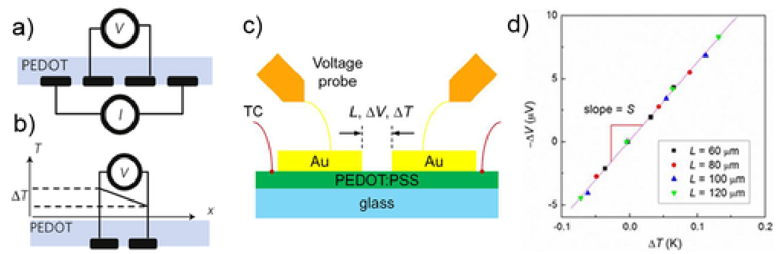
	 4. Power generation simulated versus experimental: 
Notes	● FPSE are free piston stirling engines ● Micro combined heat and power is simplified to mCHP ● A stirling engine works by using heat to expand a working fluid, usually a gas ● Natural gas can be used as the heat source fuel ● Third-order models are complex models that assume more natural physical laws, and research on them is lacking ● Current models are not time dependant ● A 100 W model Stirling engine was tested ● The power generation is through 32 radially mounted magnets ● Following many natural laws such as circuit equations and the conservation of mass, they were able to make a mathematical model of the system

	- The model works on per cycle data calculation - They also modeled the magnetic forced incurred by the generator - They modeled both closed and open circuit operation - They experimentally tested both the engine with a forced movement to verify some results, and a fully assembled engine - They applied different loads and such onto the fully assembled engine - The heater for the engine was set to 600 degrees Celsius - They completed testing with the same scenarios as would be modeled, and then compared those results to the experimental results - The relationship is correct, although it isn't perfect - Helium was the working fluid - The models that compare each of the kinematic results were closely related with the modeled and experimental data - The power generated was almost double at peaks compared to the simulated expected power at those times - The efficiency was only 2.59% - The model predicted the power output to be 23.30% higher than it actually was - A lot of heat seems to have been lost along the engine walls - There were piston collisions with each other which caused difficulties
Cited references to follow up on	NA
Follow up Questions	1. Could this work with a non-free piston generator? 2. Could this model work with modeling a regular internal combustion engine? 3. Why was the efficiency so low? 4. How does the efficiency of this engine compare to the efficiency of thermoelectric generators?

Article #23: Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity Directly and Efficiently

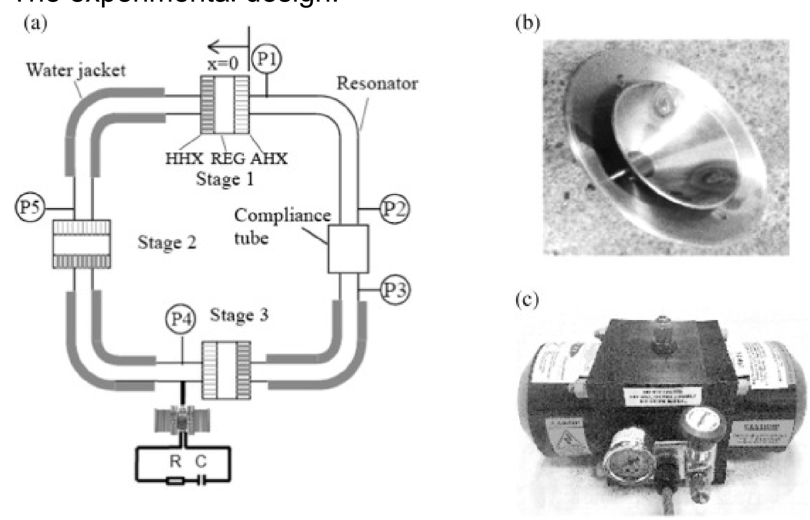
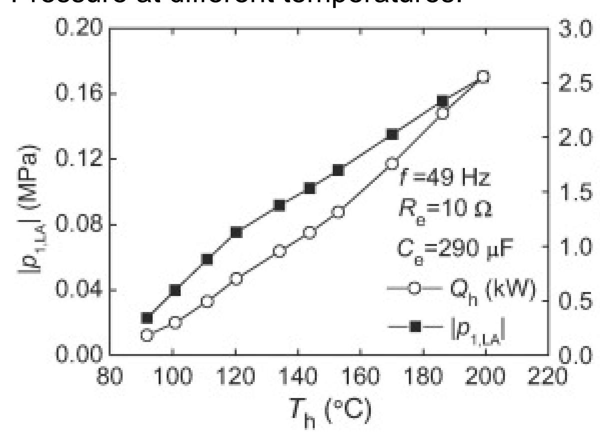
Source Title	Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity Directly and Efficiently
Source citation (APA Format)	Zhang, Q., Sun, Y., Xu, W., & Zhu, D. (2014). Organic Thermoelectric Materials: Emerging Green Energy Materials converting heat to electricity directly and efficiently. *Advanced Materials*, *26*(40), 6829–6851. https://doi.org/10.1002/adma.201305371,
Original URL	https://onlinelibrary-wiley-com.ezpv7-web-p-u01.wpi.edu/doi/full/10.1002/adma.201305371
Source type	Review Article
Keywords	1. Thermodynamic limit of energy-conversion efficiency: The limiting percentage of energy that can be turned from one form of energy into another, in this case from heat into another form of energy 2. Low quality heat: Heat that is usually categorized as waste heat, or heat that would be expelled into the environment 3. Carnot cycle: A model that explains how an ideal theoretical thermodynamic cycle would proceed 4. Figure of merit: A numerical value that expresses the efficiency of something
Summary of key points (include methodology)	The focus of this article was to review previous information that has been gathered about research on organic thermoelectric generators. There are multiple types of organic thermoelectric devices, but this article chose to focus on organic polymers. The problem with inorganic thermoelectric devices is that they are often heavy and brittle as they are constructed out of composite metal semiconductors. However inorganic polymers are cheap, easy to manufacture, and flexible. However, one of the drawbacks of organic polymers is that they often have a more modest power generation capability when compared to inorganic thermoelectric generators. The main factors that usually have to be considered when thinking about thermoelectric devices are the seebeck coefficient ($\Delta V/\Delta T$) and the thermal conductivity. This together creates a 'figure of merit' or power factor figure which can be used to measure how useful a

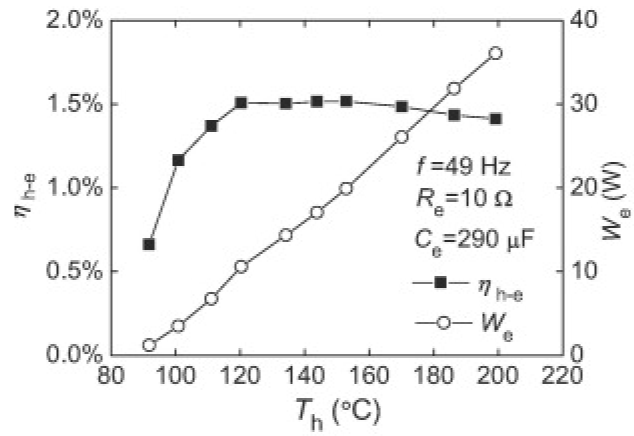
	thermoelectric device is. One of the main things that can be done to improve the performance of polymers is the use of ‘doping’. This is the name of the process when molecules and atoms are added onto a polymer chain in order to improve performance. This performance has in fact has demonstrated a large increase in performance. Additionally, another factor that is a benefit of organic polymer thermoelectric generators is that they are able to be printed using traditional printing technologies, thus saving on time, equipment, and money. All of this summarizes the current performance abilities of organic polymers and their characteristics. The authors agree with many others when they say that before the devices can become really useful, they must first be improved on the molecular level to an even higher degree.
Research Question/Problem/ Need	What recent events have occurred and what recent research has been conducted in the area of thermoelectric materials that can improve thermal to electrical power conversion efficiency and importance.
Important Figures	NA
Notes	● TEGs are limited by the thermodynamic laws as they are limited to an ideal theoretical efficiency ● A number called the figure of merit/ZT or the power factor/PF is used to measure the efficiency of a thermoelectric generator ● Most TEGs use ‘doped semiconductors’ and semimetals ● Inorganics metals have often be used but are according to the author “to heavy and brittle to be used in everyday life” ● Organic semiconductors have a high potential usability, but some drawbacks are a low Seebeck coefficient and low electron carrier mobilities. However, they are able to be changed easily through molecular chemistry ● Molecules such as fullerene and pentacene have been used to dope semiconductors ● Today the highest p-type ZT value is 0.42, while the highest n-type ZT value is 0.20 ● This article focuses on conductive polymers ● A semiconductor polymer can be used for thermoelectric generation ● Sometimes, ‘backbone’ polymers and are ‘doped’ with other materials/chemicals ● One method that works to dope polymers it to dope the long side of a monomer, and this greatly enhances electrical properties ● Additives into polymers act as thermally conductive and as electron carriers

	● There are many methods for doping polymers such as charge-annialation and solvent induced counterion removal ● Microscopic morphologies can also impact thermoelectric performance ● While usually increasing electrical conductivity decreases the Seebeck coefficient, it is possible to increase both at the same time by modulating the transport pathways of electron carriers ● Small molecules can be used for organic TEGs as well ● Organic semiconductors can have a conductivity exceeding that of silicon ● TEG devices can be fabricated using printing technologies
Cited references to follow up on	- How electrical conductivity is measured: 
Follow up Questions	1. If inorganic TEGs are undesirable why are they so often used in commercial and research applications? 2. Is there a limit to how useful organic polymers can be? 3. Are organic polymers usually dependent on petroleum for production? 4. Are these polymers toxic when used in combination with biological needs?

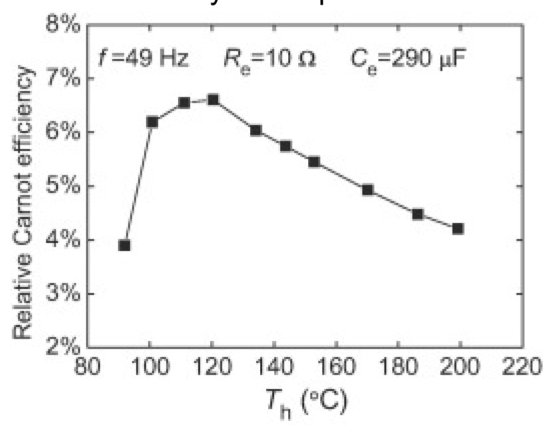
Article #24: Development of a three-stage looped thermoacoustic electric generator capable of utilizing heat source below 120 °C

Source Title	Development of a three-stage looped thermoacoustic electric generator capable of utilizing heat source below 120 °C
Source citation (APA Format)	Yang, R., Wang, Y., Jin, T., Feng, Y., & Tang, K. (2017). Development of a three-stage looped thermoacoustic electric generator capable of utilizing heat source below 120 °C. *Energy Conversion and Management*, *155*, 161–168. https://doi.org/10.1016/j.enconman.2017.10.084.
Original URL	https://www-sciencedirect-com.ezpv7-web-p-u01.wpi.edu/science/article/pii/S0196890417310166
Source type	Journal Article
Keywords	1. Thermoacoustic engine: Devices which use high power sound waves to move heat 2. Low grade heat: Heat that is not of any specific temperature that would otherwise be wasted 3. Oscillation frequency: The frequency or rate at which a wave completes a period 4. Impedance coupling: When two circuits share the same wire for a return circuit, or in other words, are at some point wires together electrically
Summary of key points (include methodology)	The purpose of this project was to design a thermoacoustic based electrical generator that could utilize heat that would be considered 'low grade' in order to generate a substantial amount of electricity. In order to do this they developed a device that utilized heat from 90°C to 200°C. This device had three thermoacoustic elements, an alternator, a resonator, and an external resistive circuit to measure power output. The working fluid in this case was a helium-argon mixture. The alternator itself consisted of a Stirling engine which was then connected to two motors. The heat source was artificial and consisted of 12 different heat 'packets'. They then tested this at different temperatures and collected several different types of data, such as the conversion efficiency and power output. The results showed that the device was producing the highest amount of power at the highest temperature, however the efficiency was more or less equal from 120°C up. Thus, there was no real benefit to increasing

	the temperature above that. Additionally, the Carnot efficiency was the highest at that same temperature. With this temperature the conversion efficiency from heat to electricity was around 1.5%, while the power output was 10.6 W. As a result of the environmental safety of this device, it has a chance to be use to utilize waste heat and low grade heat, however, the power output is fairly low for the amount of energy that it takes, and the efficiency is fairly low when compared to other electrical generators, and even when compared to a low efficiency device such as solar panels. Thus, there are better alternatives.
Research Question/Problem/ Need	How can thermoacoustic engines best be used in order to turn waste heat into electricity with the highest efficiency possible?
Important Figures	1. The experimental design:  2. Pressure at different temperatures:  3. Efficiency vs. temp:



4. Carnot efficiency vs temp:



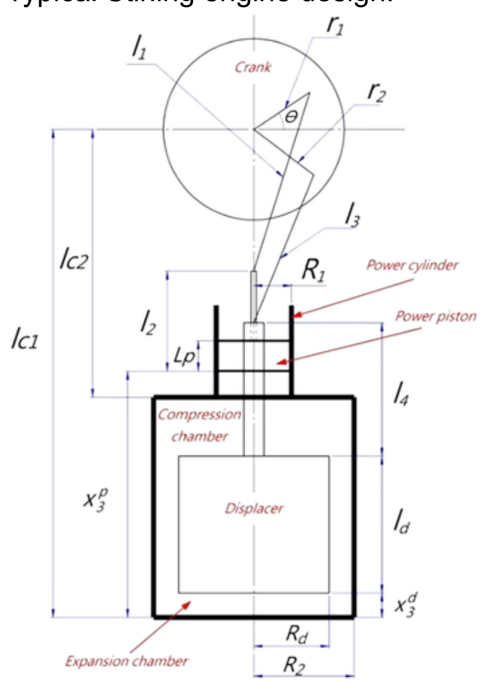
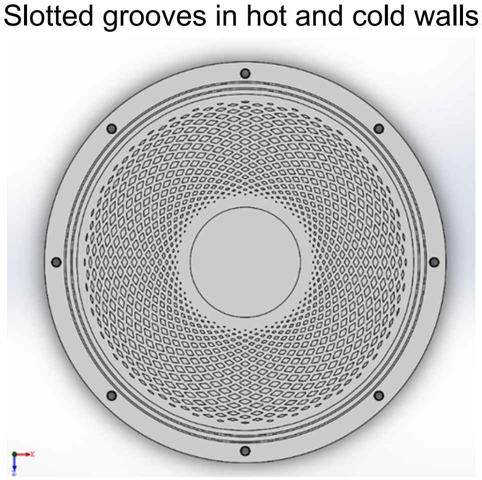
Notes

- 68% of the energy used in the US is outputted as low grade heat such as steam, and hot air
- Other methods to utilize low grade heat exist such as the organic Rankine cycle and polymer thermoelectric generators
- If heat is given to the air at the moment of the greatest condensation, or taken away at the moment of greatest rarefaction, then this causes vibration of the air
- Using some tweaks the efficiency of a thermoacoustic engine can be increased to one close to a diesel engine
- When combining an alternator (AC generator) and thermoacoustic Stirling engine and a heat of close to 650°C one group was able to achieve a 15% heat to electrical conversion efficiency
- If the amount of stages are increased, conversion efficiency can also be increased
- When more than one thermoacoustic is used and the standing wave resonator is reduce the temperature requirements are reduced to below 100°C for energy generation
- For this project a temperature range of 90-200°C will be tested

	• Three thermoacoustic devices will be used, as well as an alternator with some resistive circuits • 12 cartridge heaters supplied the heat for this project • Water cools down rejected heat and the resonator • The device operated in a loop to increase efficiency • For the operation, what is essentially a Stirling engine is used, and the working ‘fluid’ can be changed • The alternator gets some of the power every cycle • The alternator was installed at the point of highest pressure, so that the motors could be spun the most effectively • Helium or a helium-argon mixture was used in this case • Through calculations they calculated how to achieve the optimal electrical compliance as well as the optimal oscillation frequency • Through testing it was identities that although the process can occur at lower temperatures, the higher the temperature the higher the power output • The highest power output was around 20W at 153°C, with a conversion efficiency of 1.52%. • However the highest Carnot efficiency was achieved at 120°C, which was close to 6% and measures the ‘per mass’ efficiency • Overall the optimal temperature is 120°C, with an efficiency of 1.51% at which point 10.6 W were produced
Cited references to follow up on	1. G.W. Swift Thermoacoustic engines J Acoustic Soc Am, 84 (4) (1988), pp. 1145-1180
Follow up Questions	1. How does this compare to solar power? 2. Does this have a lower or higher efficiency than simply using a Stirling engine hooked up directly to a generator? 3. Would other working gases allow for a higher efficiency? 4. Could the thermoacoustic parts be hooked up to a piezoelectric element for electrical generation? Or perhaps to a ‘reverse speaker’?

Article #25: Development of a compact simple unpressurized Watt-level low-temperature-differential Stirling engine

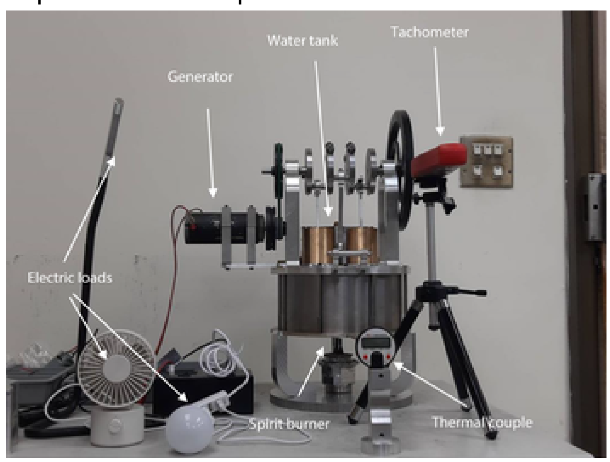
Source Title	Development of a compact simple unpressurized Watt-level low-temperature-differential Stirling engine
Source citation (APA Format)	Huang, H. D., & Chen, W. L. (2020). Development of a compact simple unpressurized watt-level low-temperature-Differential Stirling engine. *International Journal of Energy Research*, *44*(14), 12029–12044. https://doi.org/10.1002/er.5852
Original URL	https://onlinelibrary-wiley-com.ezpv7-web-p-u01.wpi.edu/doi/full/10.1002/er.5852
Source type	Journal Article
Keywords	1. Organic Rankine Cycle: The name for the thermal cycle that can be created using an organic working fluid and a heat source 2. LTD: Low temperature difference 3. α-type & β-type Stirling engines: Stirling engines that use high temperature differences 4. γ-type stirling engines: Stirling engines that operate on LTDs
Summary of key points (include methodology)	Roughly one billion people in the world lack access to electricity, and thus light at night, and a Stirling engine generator could provide this electricity using low temperature difference heat sources such as biomass, waste, and wood burning stoves which are already widely used in the third world. In order to do this the author of the article made two major changes to most LTD Stirling engine generators, they included machine drilled grooves in the hot and cold plates, and they added a regenerator. All this together allowed them to create a Stirlilng engine that used ice-water on the cold plate at 10 degrees Celsius and a burner that produced around 500W to power the device. They also created the device using a standard design for a Stirling engine. Before running tests on the device they created a simulation, and modeled the efficiency of the device. After gaining confidence with the device and seeing the power produced was in the multi-watt range, they decided to complete experimental testing. This resulted in a maximum conversion efficiency of around 0.7%, with around 4.7W being produced if running for more than an hour,

	which is 17% less than the peak if running for a short period of time. They concluded that the device is a success for multiple reasons. First of all, it was able to power multiple electronic devices, and thus it served its purpose. Secondly, while other devices of similar size produced milli-watts, this produced multiple watts. Finally, the device was able to be powered with only the heat from something simple, such as a wood burning stove, and weighed less than 5kg, so it was small, light, portable, and easy to power, and thus very useful.
Research Question/Problem/ Need	Can a Stirling engine generator be made that uses unpressurized air as a working fluid and is fairly small to generate multiple watts of electricity, so that this can be used in third world countries?
Important Figures	1. Typical Stirling engine design:  2. Slotted grooves in hot and cold walls: 

3. The results for the CFD simulation:

Case No.	T_H (K)	T_L(K)	Engine Speed (RPM)	Power (W)
1	300	500	60	3.18
2	300	500	60	2.84
3	300	500	60	0.97
4	300	500	60	1.01
5	300	400	250	4.04
6	300	440	250	6.34

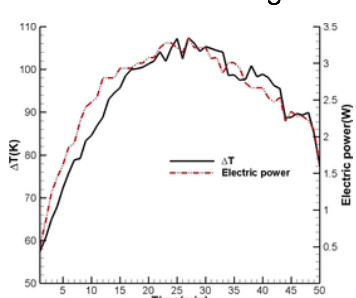
4. Experimental setup:



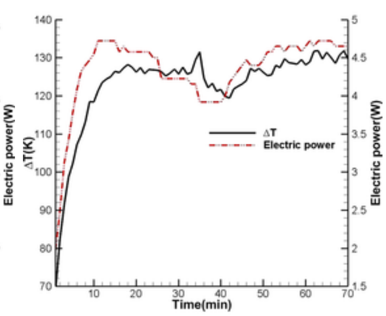
5. Power produced at different temperatures, experimental:

T_L (K)	T_H(K)	ΔT (K)	Electrical power (W)
283.02 ±0.184	353.02 ±0.104	70.00	1.58 ±0.081
282.98 ±0.104	362.96 ±0.168	79.98	2.17 ±0.130
283.02 ±0.144	373.02 ±0.152	90.00	2.86 ±0. 096
283.00 ±0.120	382.94 ±0.168	99.94	3.71 ±0. 097
283.02 ±0.144	423.02 ±0.216	140.00	5.33 ±0.144

6. Power over time using burners:



(A) Engine heated by thespirit burner.



(B) Engine heated by thegas burner.

Notes	• The authors plan on using this to generate electricity for people in third world countries • There are three main ways of generating electricity are: TEGs, the organic Rankine cycle, and low temperature difference Stirling engines • Alpha and beta type Stirling engines are more efficiency, but require higher temperature differences when compared to gamma type stirling engines • Gamma type stirling engines often have large displacer cylinders which allows for more surface area for heat transfer • γ-type Stirling Engines can be readily made from plastic • If a β-type Stirling engines is used in a truck exhaust system it can produce about 3kW • LTD sources are very easy to come buy, even in 3rd world countries • This engine is able to produce the watts with the same size as most produce milliwatts • The two main changes from the regular Stirling engine design that made this one better was the inclusion of a regenerator and slotted grooves in the hot and cold walls • The regenerator is a stack of copper wires, that releases and stores heat very quickly to act as an efficient regenerator • They simulated this using a commercial simulation software CFD • Including a regenerator sextupled the efficiency from ~2% to ~12% • The grooves increased the efficiency by about 1% • The thermal conversion efficiency was around 13%, while the overall to electric conversion efficiency was around 1.9% • Linearly, the higher the temperature the higher the power • The then tested the experimental setup after gaining confidence from the CFD simulation • Using a burner they imputed 513W of power • 65.8% of waste heat was recovered • The cold side was at around 10℃, which was done using ice cubes • The experimental overall conversion efficiency was 0.7% • When running for more than an hour the engine delivered 4.7W at a ΔT of 130K • If running consistently power goes down by 17% • A wood stove would be able to power the device
Cited references to follow up on	NA
Follow up Questions	1. Could this be shipped with helium, nitrogen, etc? 2. Could the working fluid be pressurized using a hand pump?

	3. If TEGs can produce more than a 1% conversion rate, how are Stirling engines more efficient? 4. Could a different generator be used?