

Controllable Multi-functional Heat Exchanger For Space Applications

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2014 NASA X-ploration Habitat Challenge



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Part 1

1. Executive Summary

Team Spacering will design SpaceRing, a cooling and waste heat recycling system that addresses NASA's interest for a cooling and power-generating unit in its prototype deep space habitat[1]. The merits of this system are as follows:

- Controllable cooling is critical in maintaining a habitable environment and in the functionality of life support systems, powering electronics and other devices in a spacecraft.
- Power is expensive to produce in a space environment. Converting wasted thermal energy into electricity will save energy and money for the space station.

Space habitation is a highly complex endeavor. Consequently, the SpaceRing must adhere to additional constraints, which include:

- Lack of natural fluid or gas convection due to micro-gravity environment
- Limited range for heat source and cold sink temperature
- Subject to high fluctuations of incoming thermal energy
- Minimal weight due to the high cost of transporting items into space

After consulting with NASA and experts in thermal studies, several design objectives were identified and are listed below in order of importance:

- High cooling capacity
- Reliable safety control and alert system
- Maximization of energy generation from wasted heat
- Optimization of cooling capability and power generation
- Long operational life and minimization of maintenance

In space, conventional cooling systems utilize passive heat pipe systems for small-scale heat rejection and pumped pipes with heat exchangers for large-scale heat rejection. Thermal power generation in space is mainly achieved by using thermoelectric material that produces electric energy from temperature differentials. We propose a design that combines cooling and thermoelectric power generation. Using a hot pipe connected to a heat source, a cold pipe connected to a radiator, a heat exchanger in contact with both pipes, and a pump in each pipe to move the fluid, we make an active cooling system. The thermoelectric material is inserted in the heat exchanger between the hot and cold pipes to extract energy from the maximum temperature difference coming from the two pipes. It also provides controllable cooling capacity through the use of the thermoelectric material as cooling modules.

We have tested our system under target heat source and sink conditions and measured the temperatures and flow rates. Our preliminary results are promising, demonstrating the output of 25 Watts of power on average. We are in the process of running control tests to compare the heat transfer performance without the thermoelectric generators, which is vital in determining whether or not the generators introduce an unacceptable amount of thermal resistance. While some control tests have been run already, the results have been noisy. We have modified our testing environment and data acquisition methods to allow for simple comparison between the control test results and thermoelectric performance results. Lastly, we have modified the heat exchanger design slightly to include acrylic baffles. This will allow the heat to flow through the heat exchanger more efficiently. We have presented our preliminary results to NASA and will deliver the final product by the end of May 2014.

2. Introduction

Efficient power consumption and production is a priority in any application, especially in space applications where energy is costly. For instance, the International Space Station currently requires 2 kW to drive a closed loop heat exchanger that removes 74 kW of thermal energy[2]. A heat exchanger is essential in cooling electronics and other important systems in space applications. However, currently the waste heat is radiated out to space and thus completely unharnessed. Thus, if we are able to harness electricity from the displaced thermal energy in a fashion that does not disrupt the operation of the heat exchanger, we can improve efficiencies in power consumption and production. In order to control the power used and the amount of thermal energy displaced, we design a cooling and waste heat recycling system using thermoelectric generators, which will be applied to heat exchangers.

The key idea behind our design is thermoelectric generators, which convert heat into electrical energy via temperature differentials. The power is generated via the Seebeck effect, which essentially induces electrons to flow from the hot to cold end of the thermoelectric material, thereby creating a current[3]. While the efficiency of thermoelectric generators is low compared to traditional heat engines, they have high reliability because they contain no moving parts. Furthermore, the development of high performance thermoelectric materials is an ongoing area of research, making the choice of thermoelectric generators a tractable long-term design solution.

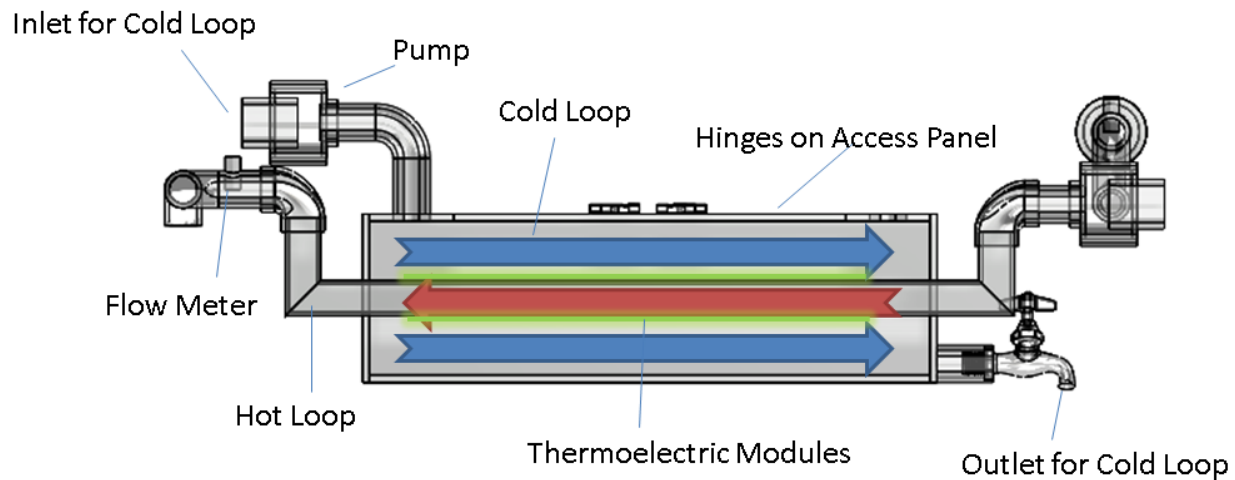


Figure 1: Overview of the heat exchanger integrated with the thermoelectric materials

The thermoelectric generators will be implemented into our design in a counter-flow heat exchanger. The thermoelectric generators will be placed between the hot and cold fluid loops in order to take advantage of the temperature differences from the electronic heat sources and the cooled radiator. The major validation criterion for our design is the ability to control the heat exchanger, specifically its power generation component. The thermoelectric generators act as thermal resistors in the heat exchanger, thus reducing the heat transfer capabilities[4], so we must ensure that this reduction has a minimal impact.

This design will be implemented as part of the NASA X-Hab 2014 Challenge. Furthermore, one of the main merits of this design is that it can be retrofitted into existing active cooling systems on other spacecraft, as only the heat exchanger portion would have to be fitted to include the thermoelectric generators. In the remaining sections of Part 1 of this report, we will introduce our approach and process in selecting a design for the cooling and waste heat recycling system. In Part 2, we will provide a detailed description of the final design of the system including CAD models and circuit schematics. In Part 3, we conclude with results that we obtained from our implemented prototype of our final design along with recommendations for future work.

3. Design Strategy

In this section, we introduce our methodology of approaching the design of a cooling and waste heat recycling system. We first introduce the criteria that we seek to implement in our design and then go through a quick overview of our chosen design and alternative designs that we have considered.

a. Detailed Design Criteria

Criteria 1: Meeting Cooling Requirements: This criterion is the most critical requirement as it aligns with our problem statement, and because other systems heavily depend on this. Failure to achieve this criterion will overheat the system.

Target: For our final design, we would like to be able to remove 100 Watts of heat from the system.

Measurement: Given a heat source in Watts, we want to know how many Watts can be dissipated. We will test the heat rejection capacity by measuring the temperature change across each inlet/outlet of the heat exchanger using a thermometer as well as the flow rate in each pipe using a flow meter. This will allow us to calculate the heat transfer in the heat exchanger.

Criteria 2: Efficiency of Power Generation: We would like to have power generation efficiency to be greater than 5% of Carnot efficiency.

Target: 5% of the heat transferred through this system will be converted into electricity under a heat source of 95°C and a heat sink of 5°C.

Measurement: Measure the power generation output recording the current and voltage through a simple circuit with a resistor.

Criteria 3: Cost: We cannot exceed the allocated budget of \$.

Target: Less than \$

Measurement: Given a design, we will estimate the price of the design by making a purchase list for constructing the prototype, testing environment, and other costs incurred.

Criteria 4: Low weight (kg): According to our astronaut advisor, it costs \$ per 1kg of cargo into space. Therefore, we would like to minimize the weight of our design to make it economical. This will have a secondary effect of increasing portability.

Target: <100 kg

Measurement: We will weigh the system using a scale.

Criteria 5: Optimization of the trade-off efficiency: Since there is trade off between the power generation and the cooling power of the system based on the functionality of the thermoelectric materials, we want to easily control the system to meet the customer's needs.

Target: The control system should find an optimum trade-off between cooling capability and power generation. Also, a manual control should be implemented if the customer wants to control the target temperature or power generated.

Measurement: We will design a control circuit and a control algorithm to determine the optimum point. It should meet the customer's need within a range. Also a user friendly GUI should be developed.

b. Explored Solutions

Chosen Design

Higher-Level System Architecture

In this system (as shown Figure 2 below) we have three mechanical subsystems that we can separately build in sequence: The hot pipe, the cold pipe and the heat exchanger. Other than the mechanical system, we will have an electrical control system that can gather sensor data from the mechanical system and control the operation of the heat exchanger through the thermoelectric generator (TEG) and the pressure release valves.

The pumps connected to the pipes will drive the hot and cold fluid and the whole system will be a single-phased system with water as the fluid inside the pipes. The water will gather heat from the heat source and bring the heat to the heat exchanger in the center. Then the heat will be transferred to the cold pipe, and eventually will be rejected through the cold sink.

More details of the mechanical system and the electrical system are explained in the following pages.

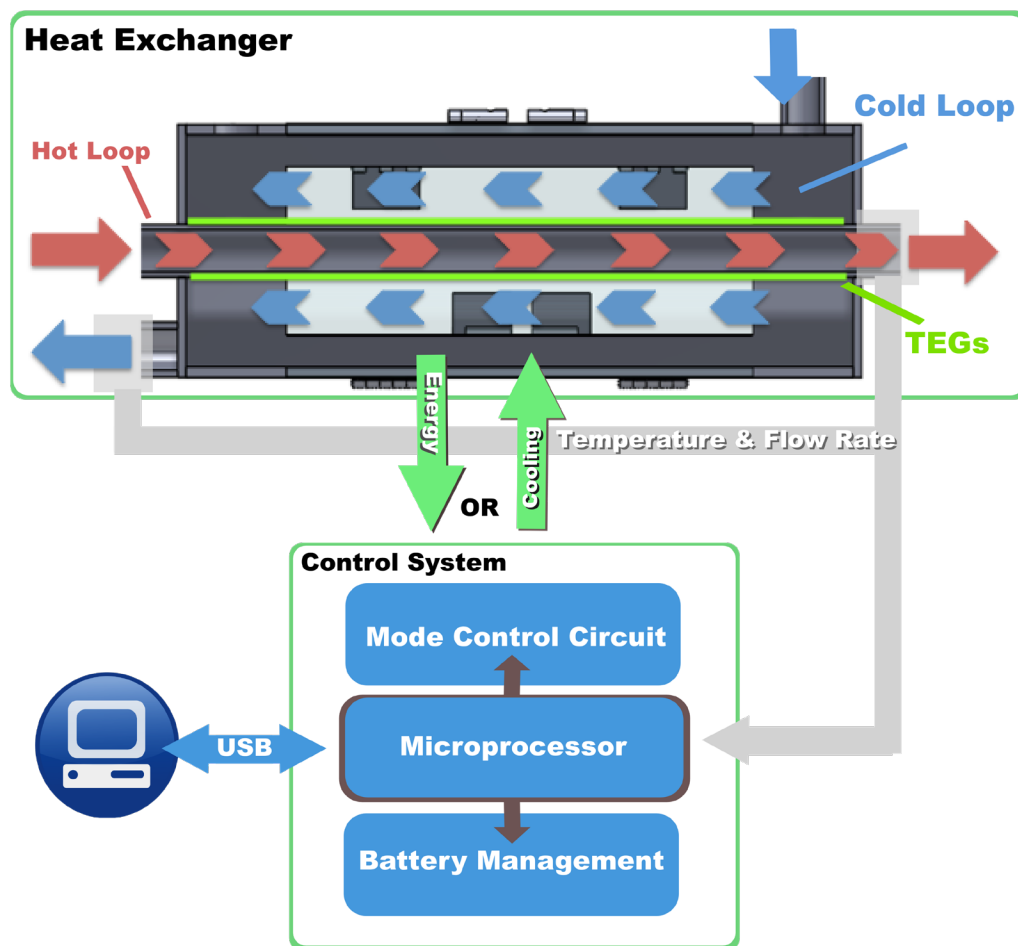


Figure 2: The preferred solution: Heat Exchanger and thermoelectric material

Mechanical System

As the CAD drawing (Figure 3 shown below) shows, our design will have the hot pipe connected to the hot source, which is a water boiler producing hot water at around 95C, and the cold pipe connecting a water chiller, which is around 5C. The heat exchanger is inspired by the tubular heat exchanger design. However we use a square hot pipe completely enclosed in chilled water on the outside, which will be within the cold pipe. The hot pipe fluid will transfer heat through to the cold pipe and transmit this radially as all sides of the inner pipe will be enclosed by chilled water.

At the point of contact of the surface of the hot pipe and the cold fluid within the cold pipe, we place a series of thermoelectric material. This will be done so that a temperature difference is formed between the faces of the thermoelectric material – one face will see the hot temperature of the hot pipe, while the other will see the cold temperature of the chilled water. In this way, we harness energy from the heat exchanger system.

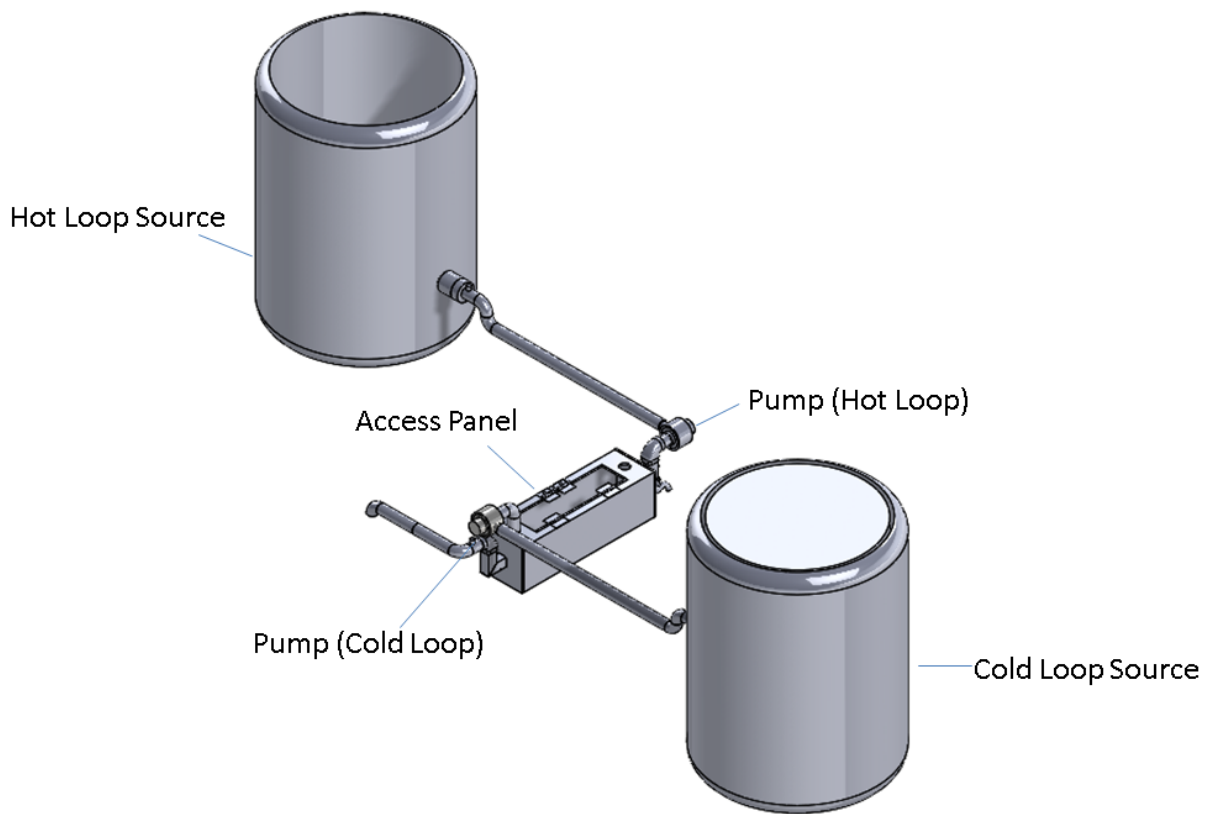


Figure 3: Overall Mechanical System

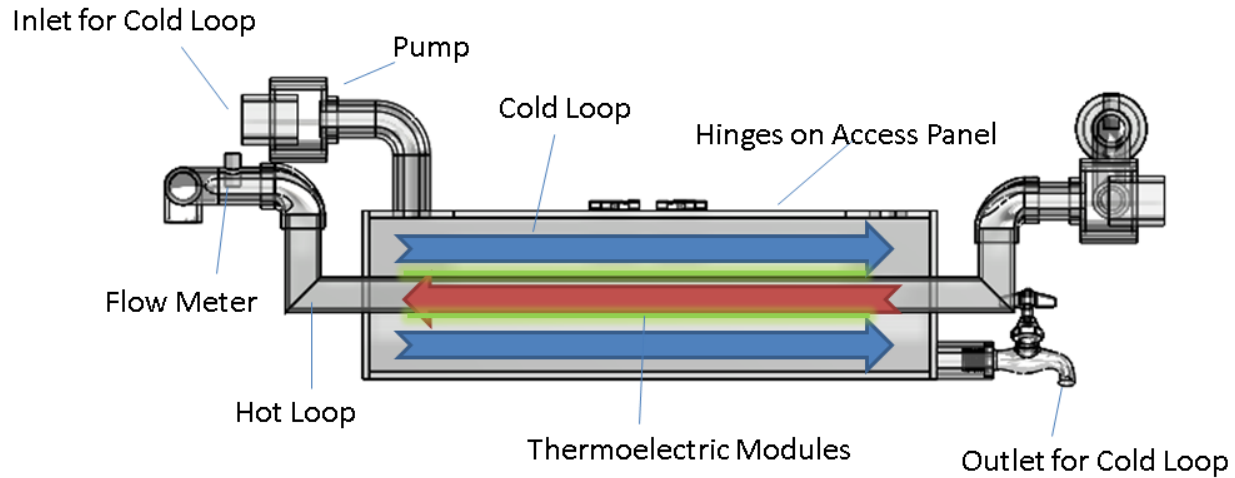


Figure 4: Thermoelectric Material in between inner square tube

Electrical Control System:

The electrical control system has three parts: the software PC Client, the control system, and the power source/storage. The microprocessor in the control system gathers data from the pressure sensors, temperature sensors and flow meters. It sends all the data to the PC client and the user decides what to do. For example, if the user thinks that the cooling power is not enough, the PC client will send the feedback to the microprocessor, and the microprocessor sends a control signal to the TEG control circuit. After that the TEG control circuit will increase the input voltage of the TEGs so the TEGs will increase the heat transfer, and thus increase the cooling efficiency of the system. If the user wants to generate more power, the microprocessor changes its control signals and energy will be gathered from the TEGs. The voltage and current from TEGs will go through the battery management circuit that consists of maximum power point trackers, boost buck regulators and a battery charging system. In the end the energy will be stored in batteries[5].

Also, since the control circuit could control whether the TEG should generate power or consume power and enhance the cooling capacity of the heat exchanger, we can design an algorithm to optimize over this tradeoff between enhanced cooling and power generation. In this way we can change the performance of the system according to customer's needs.

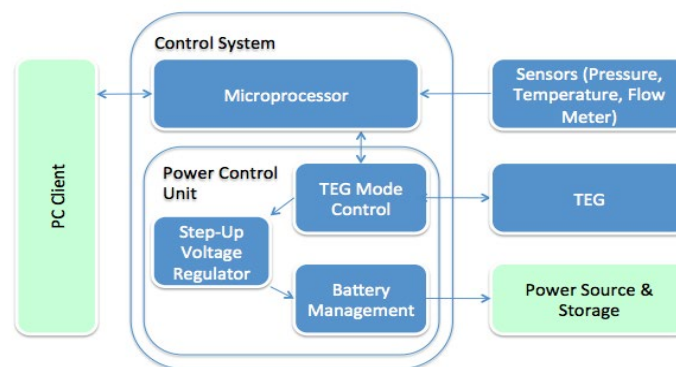


Figure 5: Electrical Control System Schematics

Other Brainstormed Solutions

Rotational Ring

The first design is called a Rotational Ring. As the name suggests, the device will be powered to rotate. When the gas in the top chamber expands to a certain threshold pressure, the pressure release valves open and allows the gas to pass through a turbine generator. The gas then moves to the cold chamber as illustrated in Figure 3.7.

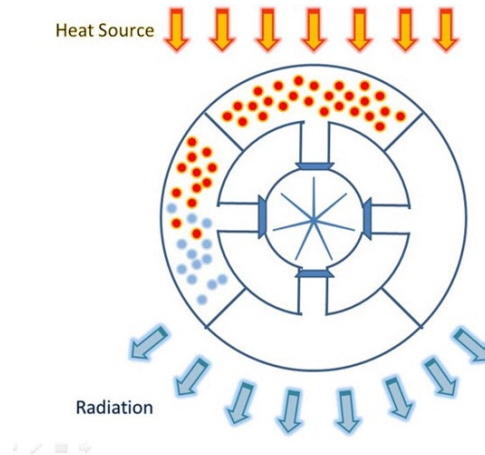


Figure 6: Rotational Ring Schematic

Stirling Engine

The second design is based on a Stirling Engine. As illustrated in Figure 7, shafts of a flywheel, which generates energy as it spins, connect the two pistons. The flywheel is driven by air expansion in the hot chamber and the air contraction in the cold chamber.

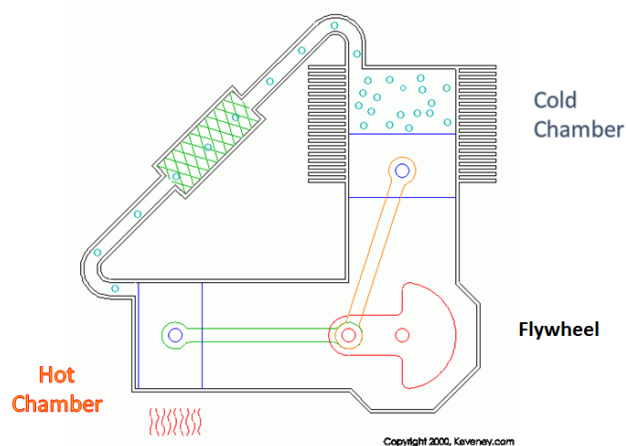


Figure 7: Stirling Engine Schematic

Solar Updraft Tower

In the third design, when the gas in the bottom is heated, it expands and spins the turbine at the top. Then the gas is in contact with the cold walls, where it contracts and circles back to the base from the sides.

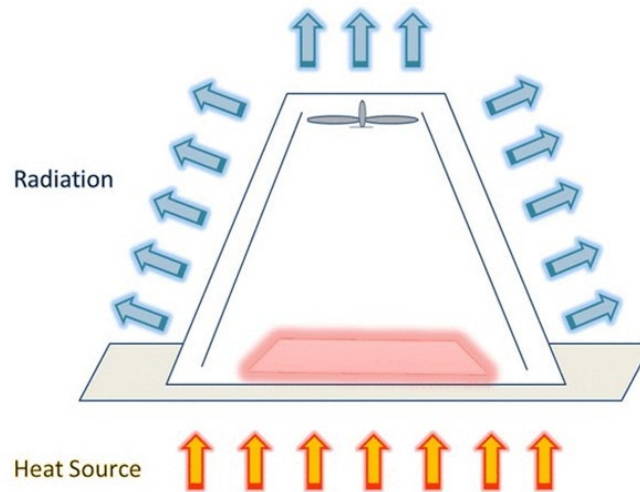


Figure 8: Solar Updraft Tower Schematic

c. Decision Analysis

Selection of the higher-level mechanical system

In order to evaluate our brainstormed solutions, we put them into the screening matrix shown in Table 1. We set up the Stirling engine as the reference solution. Compared with the Stirling engine, the rotational ring and the heat exchanger have better cooling power. For the power generated, the Stirling engine has the best efficiency, which is around 20%. As we can see from the table, the heat exchanger design and the Stirling engine have better features than the other two, so we place them into the scoring matrix.

Criteria	Rotational Ring	Stirling Engine	Solar Updraft Tower	Heat Exchanger
Cooling Power	+	X	-	+
Power Generation Efficiency	-	X	-	-
Weight	-	X	+	-
Safety	+	X	-	+
Simplicity	-	X	-	+

Table 1: Pugh Screening Matrix

We then used a scoring matrix to evaluate our remaining options: the Stirling engine and the heat exchanger (as shown in Table 2). We give weights to the criteria based on how important each criterion is. Then, we rate each option from 1 to 5, 1 being the lowest score and 5 being the highest score for each criteria. Since we are designing a cooling system, the cooling power is given a higher weight than the others. Another crucial criterion is the complexity. The heat exchanger doesn't have any moving parts, so it beats the Stirling engine in complexity. In the end, as we calculated, the heat exchanger has a score of 3.60 and the Stirling engine has a score of 3, so the heat exchanger with the thermoelectric generator is our preferred design.

Evaluation Criteria	Weight	Stirling Engine		Heat Exchanger	
		1-5	weighted	1-5	weighted
Cooling Power	30%	2	0.6	4	1.2
Power Generation Efficiency	20%	5	1	2	0.4
Weight	10%	3	0.3	2	0.2
Safety	10%	2	0.2	3	0.3
Simplicity	30%	3	0.9	5	1.5
Total weighted Score	100%		3.00		3.60
Rank			2		1

Table 2: Pugh Scoring Matrix

Trade-off between cooling capability and power generation

Another design decision we would have to make involves the trade-off between cooling capability and power generation. The more thermoelectric material we place in the heat exchanger the more power we can extract, but in doing so the heat transfer from the hot pipe to the cold pipe would be sacrificed since the thermoelectric material presents additional thermal resistance to the heat exchanger. This decision will be made after further prototyping and testing. We will measure heat transfer performance with and without the TEG to determine the loss of heat transfer due to additional thermal resistance, and then calculate additional radiator surface area needed to compensate loss of heat transfer. Ultimately, a matrix describing the tradeoff between cooling capability and power generation ability would be one of our final deliverables in addition to our prototype, since the level of importance of power and cooling is different for different space missions.

Capillary Wick Decision

After contacting manufacturers about purchasing the capillary wicks, we discovered that these capillary wicks were far too expensive. Thus, we relied on pumps to drive the fluid through

the pipes. However, in calculating the capillary pressures and flow rates that could be provided by capillary wicks, we found that the capillary wicks would actually provide a flow rate that could generate a power output close to our target efficiency at the given temperature range. Therefore, in the space NASA can consider the design using capillary wicks. Detailed calculations and explanations are in the Appendix.

Phase-change System Implementation Decision

One important problem that surfaced after we decided to not use capillary wicks is that we needed to address the issue of including a system that would rely on the phase change of the working fluid. From Table 3 below, we can see that the advantages of using a phase change system include:

1. The temperature difference is not limited by the boiling point and freezing point of the working fluid, thus the efficiency is larger
2. The weight of the system under the same dimensions will be lighter because the volume of gas would be lighter than liquid.

However, the phase change system requires the use of a capillary wick. Furthermore, high temperature and high pressure steam is very dangerous. Also, it is hard to scale the phase change system because we would need to design the parts specific to the gas and liquid separately. With a phase change system, if we can prove that the current system is valuable, it is easy for NASA to implement the same design in space.

	Phase Change	No Phase Change
Temperature difference	Large	Small
Requires capillary wick	Yes	No
Complexity	High	Low
Safety	Dangerous	Safe
Maintenance	Hard	Easy
Weight (under the same dimensions)	Light	Heavy
Scalability	Low	High

Table 3: The trade study of selection between a single or double phase system

Detailed System Design Selection

After deciding on the capillary wicks, we considered two designs for the current system. The first one was to add pumps into the system so the pumps can directly drive the fluid around. The second one was to use a thermosyphon design. The thermosyphon utilizes natural heat

convention to drive the fluid. Between these two, we made a decision matrix for the advantages and disadvantages of both designs. As Table 4 indicates, the pumps have more moving parts and are not passive. However, since pumps are easily controllable, we can shut down the whole system if a component is damaged or stops functioning. With thermosyphons there is no way to control the flow-rate or pressure of the fluid. Hence, out of safety issue we decided to use pumps.

	Pumps	Thermosyphon
Moving parts	Yes	No
Passive	No	Yes
Depends on Gravity	No	Yes
Complexity	Low	High
Easy to modify and control	Yes	No

Table 4: The trade study of detailed system design selection

d. Timeline

After the analysis of the various design components and coming to a conclusion on the decision of design details, we followed the tasks and timeline reproduced below. The highlighted text shows the important deadlines that we had with NASA and the Senior Design course. Please refer to the Appendix 2 for a detailed Gantt chart.

Regular Activities

Organize meetings and write weekly updates reports to mentors
 Tuesday Team Meetings
 Friday Meetings With Mentors

Prepare For System Definition Requirements(11/08/2013)

Developed mission statements
 Background Research
 Meeting with NASA to ask for their needs
 Brainstorm Ideas
 Calculate efficiency for each design
 Developed objectives and criteria
 Meeting with astronauts, National Instruments and Texas Instruments for resources
 Plan for the budget
 FOSS 1 goals and evaluations
 Design Context Review
 Produce need to know list and do literature review
 Prepare for SDR presentation to NASA
 Construct Pugh Matrix and Gantt Chart ; Manage SVN
 Prepare for project pitch presentation(11/01/2013)

SDR presentation to NASA

Prepare For Preliminary Definition Requirements(12/09/2013)

Construct FKA spec sheet(11/11/2013)
 FOSS 2 goals and evaluations
 Make CAD Model for Heat Exchanger
 Design Pressure Module for Control System
 Design flow-meter Module for Control System
 Design Temperature Module for Control System
 Fluid Simulation with CAD Model
 Order Materials
 Prepare for PDR presentation to NASA
 PDR presentation to NASA and Final Presentation(12/09/2013)
 Binder Documentations for Cycle II(12/16/2013)
 Test For TEG
 Design and construct the first heat exchanger prototype
 Prepare for final presentation(12/09/2014)
Revised Team Contract & Cycle 3 Objectives Due (1/17/2014)

Prepare For Critical Design Review(02/10/2014)

Construct test environment
 Make CAD Model for the system
 Design and build the circuit for Control System
 Build user interface for test
 Construct prototype for the subsystems
 Put the sensors and test for the subsystems
 Prepare For Critical Design Review
 Critical Design Review presentation to NASA (02/10/2014)
 Finish Final Design
 Elevator Pitch
 Implement safety controls
Cycle 3 Documentations Due (2/21/2014)
Cycle 3 Evaluation Due (2/25/2014)

Prepare For Design Show Case(04/17/2014)

Test the overall circuit
 Check point presentations to NASA
 Refine Final Design if needed
 Build the final design prototype
 Test for the system
 Develop an optimization algorithm
 ECE Affiliate
 RURS
 Design Show Case
Cycle 4 Documentations Due (4/21/2014)

Prepare For Final Presentation(04/25/2014)

Improve system efficiency
Cycle 5 Documentations Due (4/25/2014)

Part 2

4. Final Design

a. Mechanical System

Heat Exchanger

The heat exchanger utilizes two different materials for the hot and cold pipe. The cold fluid pipe has no material constraints dependent on the temperature that it will operate under; therefore we will use acrylic in order to construct the rectangular box that outlines the large outer piping. For the hot pipe we will use steel wide enough to place our TEG modules on.

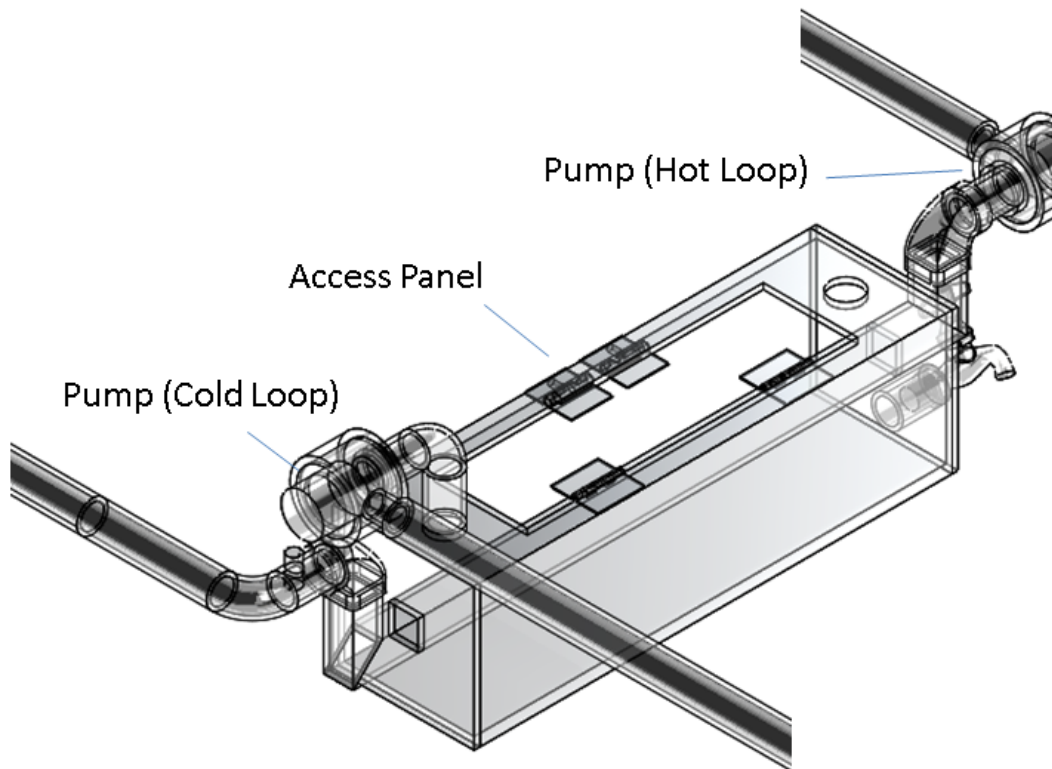


Figure 9: Angle view of Heat Exchanger depicting the solenoid valves and pumps

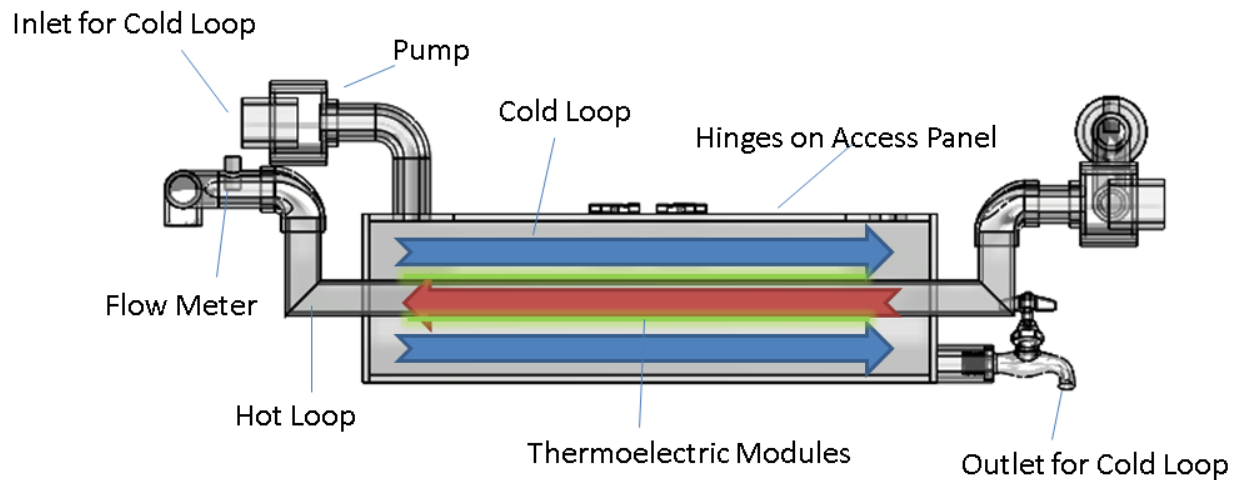


Figure 10: Side view of Heat Exchanger depicting fluid flow direction and flow-meters

The heat exchanger is 48 inches in length, and consists of two square copper pipes. Fluid from the hot pipe and the fluid from the cold pipe come in from the opposite end of the square tubes in order to achieve maximum heat exchanger through counter-flow configuration. Thermoelectric material is placed in between these square pipes, as shown in the Figure 4 below. The square tube is 1.25 inches in width inside of the tube, and the wall thickness is 1/64 inch on all four sides.

As explained in the chosen design section of 3.b of Part 1, the TEG is placed in between the hot pipe and the cold fluid within the cold pipe. The temperature difference between the surface and the chilled water will drive the TEG to output power, which will go to the TEG mode control circuit of the electrical control system. In another mode, the TEG will create a temperature difference to the heat load created by the chilled water and the hot surface of the hot pipe. This will enhance the heat exchanger cooling capacity.

The fluid within the cold and hot pipes will be driven in a counter-current fashion so that the temperature difference across these pipes will be nearly constant. If we were to run the fluids concurrently, then the temperature difference going across the TEGs will be different and thus be harder to manage. Since each TEG module will be wired in series, if one module performs more poorly than the others, then the output of all the other modules will be affected. Thus, a concurrent flow configuration may be detrimental to power generation.

b. Electrical Control System

The control system consists of the following general units:

1. The microcontroller unit and the interface to a PC Client
2. The TEG Mode Control circuit
4. A power management system

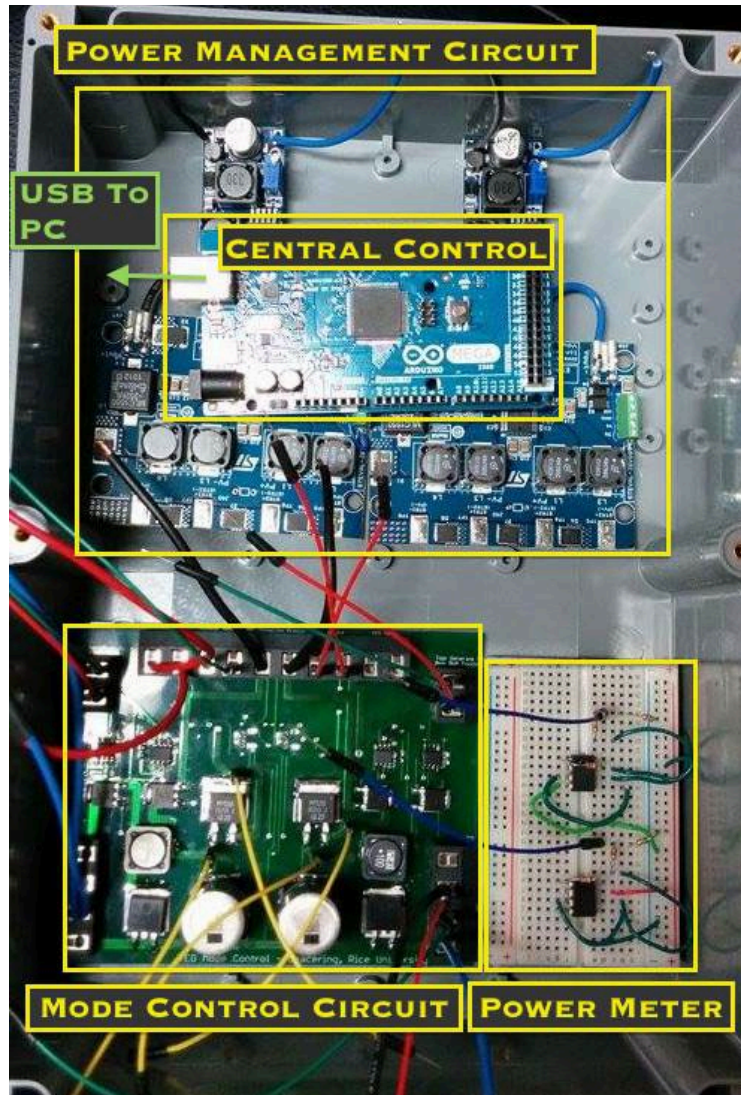


Figure 11. The electrical control system

Microcontroller

The microcontroller unit acts as the interface between the sensors, TEG and the PC client. The microcontroller unit should have enough I/O pins to connect to 8 different sensors, or more if you would like to account for redundancies in the sensor system. The microcontroller should also have at least two pins with a PWM channel and another pin reserved for connection to the TEG Mode Control circuit.

The microcontroller connects to the PC Client via USB and control of the microcontroller will occur via a user interface on the PC. More on the PC Client User Interface will be discussed later. Another part of the microcontroller is to incorporate a control algorithm that will keep the outflow temperature on the hot side in the heat exchanger constant, and to find a maximum output power point with the TEG modules – therefore when considering the implementation of this design, we will make sure to use a microcontroller with enough program memory.

TEG Mode Control Circuit

Electronics and other sources of heat will fluctuate in temperature, and will be seen as a variable heat load from the heat exchanger. A hotter fluid at the inflow of the hot pipe will cause a greater transfer of heat to the cold pipe. This larger heat transfer will cause a greater fluid temperature within the cold pipe and thus radiate more thermal heat out to space, due to Stefan-Boltzmann's law. If we would like to downsize the radiator, which will decrease the cooling caused by radiation, we will have to add an additional mechanism to cool the hot side working fluid. By utilizing the thermoelectric cooler (TEC) capability of the TEG modules, we can cool the working fluid at the hot loop even with the limited radiator size. Placing a temperature sensor at the inflow of the hot pipe on the heat exchanger, and having a flow meter at the inflow, we will be able to calculate the required adjustment to the TEG/TEC modules in order to compensate for the additional heat load.

In the case of lower heat load coming from the heat source than expected, we will have no reason to switch any of the TEG modules to a TEC unit, and therefore, we can have the system run to harvest the most power that it can from the given temperature difference. In the case of a higher heat load than expected, we will need to use part of the TEG modules as a cooling unit and will input current into one array of TEG modules. We invoke a KIP controller which takes the safe hot flow outlet temperature and its actual temperature to update the cooling power. It will keep increasing the cooling power as long as the temperature stays above the safe temperature. On the other hand it switches back to power generation mode when the temperature drops below the safe threshold.

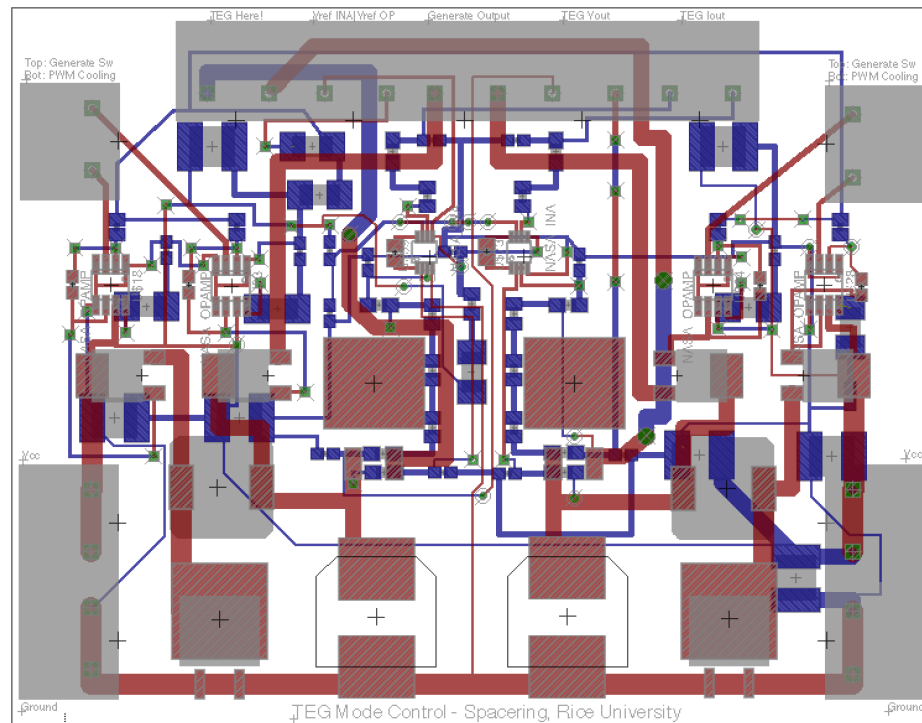


Figure 12: The TEG Mode Control circuit, which connects to the TEG and the microcontroller, the Boost Converter and the Battery Management circuit.

In order to switch the TEG modules from TEG to TEC functionality, we construct a separate circuit that we call the TEG Mode Control circuit. The TEG Mode Control circuit is essentially a buck converter with the addition of two transistors that act to 1. control the input current to the TEG modules, and 2. control the state of the TEG as a power generating module or a cooling module (see Figure 2). The figure illustrates that the input going to the buck converter is a PWM signal, which based on its duty cycle will produce a certain average voltage in between GND and V_{cc} at the output of the buck converter. This controllable voltage is the signal that is fed to the TEG module when the TEG module is in its cooling mode.

When the TEG is in its cooling mode, the second transistor will be off to disconnect the TEG from the , which eventually leads to the battery management circuit. If the TEG is in its power generating mode, then the TEG will go to the power management circuit and the voltage produced from the TEG will charge a battery.

Power Management Circuit

In order to extract the maximum output power from a series of TEG's, we will need to utilize a maximum power point tracker in conjunction with the battery management circuit. Whenever the TEG mode control circuit operates the TEG modules in power generation mode, the output of the TEG modules will go to a maximum power point tracker, which essentially matches a load resistance equivalent to the internal resistance of a TEG to achieve the optimal power. The internal resistance of a TEG can easily change, and the voltage output from the TEG can change as well, so the maximum power point tracker will match this changing required load for the TEG. The output from the maximum power point tracker ranges from 3V to 38V and it will then go to a boost buck regulator that outputs constant 14V, and this will lead to a battery charger.

c. Sensor System

The sensor system consists of three different types of sensors, which all should be compatible within the working temperature of the working fluid at the hot and the cold end of the heat exchanger. Without redundancies there are two flow meters and four temperature sensors. Due to the open loop configuration of our prototype, we do not include pressure sensors. Please refer to the Appendix for more on temperature sensor placement.

In additions to specialized sensors, we also implemented 0.01ohm shunt resistors directly to the TEG i/o lines to measure the voltage and current going through the TEG. We constructed a 1/6 voltage divider in order to scale the TEG voltage (0 to 30V as we measured) to 0 to 5V Arduino measurement range. We used INA 126P with V- set to ground, V_{ref} set to one terminal of the shunt resistor and a gain of 180 to amplify the voltage drop across the shunt resistor. This setup also guaranteed that our output voltage stays within the linear range centered at the common mode. We can subtract the V_{ref} using the voltage measured the voltage divider mentioned above and then compute the current.

5. FDA Approval

Our design is an aerospace oriented application that does not contain any biological process and only interacts with a human operator through PC clients. Thus, FDA approval is not required. Also, since our design is a proof of concept for the NASA deep space habitat competition, the ISO or other market related approval is not required either. We have our presentations to NASA professionals every month to report our results to them.

6. Cost of Manufacturing

In the table below we list the parts list of all the different components that went into this design. If carefully optimized, reuse of materials for additional production of our prototype will decrease the total price.

Item Name	Unit Price	Quantity	Total Price
El sid pumps 3.5 Watt 12 Volt		2	
Type 304 Stainless Steel Threaded Pipe Fitting		15	
Standard Wall-Type 304/304L Stainless Steel Thread Pipe Nipple		8	
Quick-Disconnect Latch Hinge		4	
Arduino Mega 2560		1	
Dri-box 330 Outdoor Waterproof/Weatherproof Box-Black		1	
DROK 120W 12V/24V/48V 10-32V to 35-60V DC Converter		2	
SMAKN Dc Boost Buck Converter 3-35v to 1.2-30v Solar Voltage Regulator Power Supply		2	
Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1" Solid Extrusion		2	
Aluminum Inch T-Slotted Framing System L bracekets		30	
Standard Zinc-Plated Steel End-Feed Fastener, for 1" Aluminum Inch T-Slotted Framing System		30	
Type 304 Low-Pressure Stainless, Steel Threaded Pipe Fittings, 3/4"		8	
Auto Boost Buck Regulator		2	
Waterproof connector		2	
AC Adapter		2	
Power Resistor		2	
Power Inductor		2	

1-3/4" SQ {A} x 1.620" ID {B} x .065" Wall {C} Square Steel Tubing		24 in	
Type 304 Stainless Steel Threaded Pipe Fitting, 1 Pipe Size, 90 Degree Elbow, 150 PSI		2	
Slit Self-Seal Polyethylene Pipe Insulation, 1/2" Thick, 7/8" Insulation ID, 6' Length, Black		1	
N-Channel MOSFET		4	
Voltage Regulator Step Up		2	
Shottky Diode		2	
Printed Circuit Board		2	
Thermoelectric Generator Modules TG-12-8 module		40	
Item Name	Unit Price	Quantity	Total Price
Stop Cock		1	
Faucet		1	
Total Price of Prototype			

Table 5: List of expenditures for the prototype.

The most expensive component of our design is the thermoelectric generator (TEG) modules, which were outsourced from a third-party vendor, Marlow Industries. Therefore, although there may be a small price reduction, around 10%, if we buy TEGs in very large quantities, we do not expect the price of TEGs to decrease significantly. On another note, our design is meant for customized installation in space applications, therefore we do not expect large scale manufacturing production.

Part 3

7. Design Performance

Heat Exchanger Test:

We have proceeded with testing since the final heat exchanger design was implemented with the sealed TEG modules in place in Cycle 4. We tested the TEG power generation and cooling capacity. We measured the inlet and outlet temperature of the cold and hot loops first with handheld thermometers and later with the temperature sensors connected to the PC client. Flow rates are measured through the two flow meters connected alongside the pipes and the data from the flow meters is outputted to the PC client. These values are used to calculate the heat rejection from our system. We measured the open circuit voltage of the TEGs and used the TEG datasheet to estimate the optimal power output. We conservatively calculated the TEG absolute efficiency using the ratio of optimal power output to the total heat rejected from our system. The percentage of Carnot efficiency is based on the absolute efficiency to the Carnot limit at our operating temperature.

Hot Inlet Temp (C)	Hot Outlet Temp(C)	Hot Flow Rate(L/sec)	Cold Inlet Temp(C)	Cold Outlet Temp(C)	Cold Flow Rate (L/sec)	Heat Xfer (Hot, W)	Heat Xfer (Cold, W)
63	49.31	0.0041	3.19	10.25	0.0237	234.956	700.41
63	50	0.0041	2.88	10.31	0.0237	223.114	737.117
81.5	64	0.0031	0.37	7.13	0.0206	227.091	582.926
91.7	75	0.0031	1.5	12.75	0.0258	216.709	1214.99
100	79.81	0.0052	1.94	11.5	0.0237	439.48	948.43

Table 6: Testing Results with TEG

Hot Inlet Temp(C)	Hot Outlet Temp(C)	Hot Flow Rate(L/sec)	Cold Inlet Temp (C)	Cold Outlet Temp (C)	Cold Flow Rate (L/sec)	Heat Xfer (Hot, W)	Heat Xfer (Cold, W)	TEG Opt Power (W)	% of Carnot Efficiency
61.7	51.19	0.0041	3.25	9.31	0.0258	180.37 ₉	654.473	7.1691	22.77%
61.7	52.6	0.0031	3.25	7.44	0.0186	118.08 ₇	326.232	7.1691	34.78%
80	65.94	0.0056	3.94	8.3	0.0206	329.58 ₉	375.97	9.6838	13.64%
80	66.44	0.0041	3.94	8.44	0.0155	232.72 ₅	291.974	9.7056	19.36%
100	78.06	0.0021	5.13	10.63	0.0289	192.86 ₆	665.365	12.846	26.20%

Table 7: Testing Results with TEG

These results suggest that we are able to achieve on average a 5% of Carnot efficiency, which is one of our criteria. Also, we significantly exceeded our goal on rejecting 100W of heat. However, we realized that there is a lot of noise in our measurements that can come from non-constant flow rate, varying temperature at the inlet and outlet, non-ideal fluid circulation in the

heat exchanger and small electrical leakage through the water. We also discovered that TEGs connected in serials give better power generation capability.

Thermoelectric Material Test:

In order to verify the thermoelectric material performance, we purchased two pieces of thermoelectric modules from Marlow industry and conducted a test of power output vs. temperature differential between two surfaces of the TEG device. We set up a electric hot plate and ice box cold plate, matched the optimal load resistance and measured the output power at various temperature differentials. The results are depicted in Figure 13. A clear trend of power output increase as temperature differential increases is observed. This trend confirmed the spec sheet. Although we also observe 5x worse performance between our measurement and the spec sheet, we attribute this to our inaccurate experiment setup and measurements.

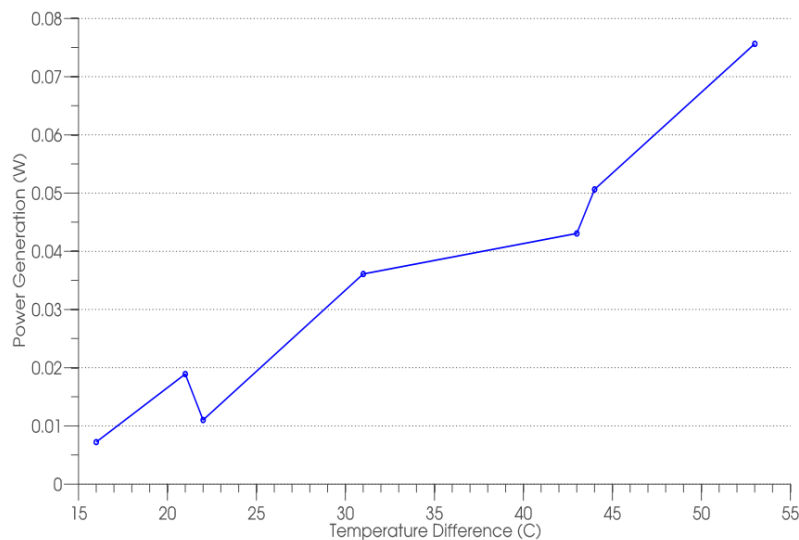


Figure 13: Thermoelectric Material Test Result: Temperature Difference vs. Power Generation

Summary and Recommendations

Currently, we have a fully functional prototype the acrylic panels are assembled and glued together and the heat exchanger is completely watertight. The pipe connections are also watertight, as they are reinforced with Teflon tape. The only portion of the system that leaks is the outlet of the water cooler, but the leakage is very slow – approximately one drop every fifteen seconds. Since we are constantly running tests on our system, we have not had time to reseal this part yet as the silicone glue takes around two to three days to dry. However, once the testing is completed, we can reseal this part.

In terms of the heat exchanger, we have successfully installed acrylic baffles that are meant to aid the flow of water and increase the heat transfer. Preliminary tests demonstrate that performance is indeed optimized with the baffles installed. The thermoelectric generators (TEGs) have been attached to the heat exchanger using twist ties. In the final configuration, the TEGs will be permanently attached in the inner pipe using thermal glue, but as our configuration is

constantly changing and we need to run control tests with the TEGs installed, we cannot permanently attach them yet.

With a hot inlet temperature of 95 C and a cold inlet temperature of 5 C, we are able to remove on average around 600-700 Watts of thermal energy. Additionally, we are able to generate around 25 Watts of power from the TEGs. We are able to achieve on average around 5% of Carnot efficiency. With the baffles installed, this figure is expected to increase, but we have only used the baffles in the control test so far.

We have met our NASA mentors a total of five times throughout the academic year so far and they are up to date with our current results. We will present our prototype to Frank Davies from the Johnson Space Center in our final design review next week as well as deliver our final report to them by the end of May 2014. This report will detail all of the work we have undertaken this semester, including test results and recommendations for the practical implementation of this system.

Included below are some recommendations that we suggest to anyone seeking to replicate our design. These recommendations come from our practical experience in designing and building our first prototype. At the time of writing these recommendations, our first prototype is complete and we have obtained our initial results.

1. **The acrylic casing of the heat exchanger should be sealed with acrylic glue and silicone glue** – the gaps between the panels of the acrylic casing are highly prone to leaking and should thus first be sealed by applying the acrylic glue using a needle applicator. After this, a layer of silicone glue should be applied on both the inside and outside of the casing.
2. **All pipe connections should be reinforced using Teflon tape** – the connections between all of the pipe connections are naturally prone to leaking unless Teflon tape is applied. This completely remedies the problem of leaking.
3. **Connections to the water cooler and heater should be reinforced using silicone glue** – the outlets of the water heater and cooler are not threaded and thus cannot easily be sealed. We have found that the best approach in this case is to use two layers of silicone glue, which prevents any leaking. *It is important to use silicone glue or another heat-resistant glue since the hot pipe contains near-boiling water, which can easily melt other glues.*
4. **TEG serial connection is more suitable for power generation and parallel connection is better for cooling** – our research shows that serial configuration of the TEGs outperforms the parallel TEG connection by more than a factor of two and the literature also suggests the same. On the other hand, parallel connection allows more current to go through each TEG module, thereby increasing cooling capacity.
5. **Counter flow heat exchanger with constant temperature difference across all TEGs are better for power generation** – in a series configuration, the power generation efficiency is determined by the worst performing module in the series. A counter flow heat exchanger keeps the temperature differential approximately uniform at different locations along the hot pipe and this enhances the worst performing module.

Furthermore, there are some more significant modifications to our design that we believe would allow for easier operation of the prototype. However, due to time constraints and that fact that these modifications are not vital, we have not implemented them in our first prototype.

1. **The acrylic casing can be modified to exclude the teeth.** In retrospect, the addition of the interlocking teeth on the heat exchanger design made it more difficult to seal the casing. If building this design from scratch, this is a decision that must be made early on since once the square-to-round adaptors are welded on to the inner pipe, it is no longer possible to make modifications to the design of the acrylic casing.
2. **Maximum Power Point Tracking System (MPPTS) should be implemented.** This is a load matching system in the energy industry that automatically adjusts the output impedance to the optimum value.

Appendix A

a. TEG Selection Documentation

We decide to use commercially available thermoelectric devices because it is infeasible for us to manufacture high quality devices. Additionally, and the price for most TEG/TECs is below 30 USD, which is very affordable given our budget.

Model	Optimal Power Output at =60C	Heat Rejection Power at input =4A
Marlow RC12-8	1.19W	50W _a
TE Tech HP-127-1.0-1.3-7	N/A	53W
Marlow RC12-2.5	0.41W	45W
Custom Thermal Electric 1261G-7L31-04CQ_R2	0.6W	N/A

Table A1 TEG performance chart

*Values are normalized to the unit device surface areas of 4cm by 4cm

When choosing the thermoelectric materials, we focus on two criteria: its optimal power output at given temperature differentials and the cooling power at a given power input and temperatures. We researched multiple companies and composed the following chart of our top candidates.

We realized that the cooling capacity across multiple devices are similar and what distinguished the device is its power generation capacity. Therefore we choose the first module in this table as our prototype thermoelectric material.

b. Temperature sensing method

Temperature Sensor Selection

Model Name	DS18B20	Microchip MCP9804
Dimensions (mm)	7 x 7 x 25	2 x 3 x 0.9
Operating Temperature	-55°C to +125°C	-40° to +125°C
Output Interface	9 – 12 bits digital output	I2C
Accuracy	±0.5°C from -10°C to +85°C	±0.25°C (typical) from -40°C to +125°C
Voltage - Supply	3.0 V - 5.5 V	2.7 V – 5.5 V
Termination Style	Waterproof Wires	Exposed pins
Sensor Type	Direct-to-digital temperature sensor	Band-gap type temperature sensor
Price		

Table A2 Temperature sensor comparison chart

We found two potential sensor candidates that can directly gather temperature data without any other equipment. The advantage of the DS18B20 is that the output interface is only one digital output wire, so compared to the two wired I2C interface of Microchip MCP9804, the probability for breaking DS18B20 is lower. If one of the two wires of the Microchip is broken, the data for Microchip is corrupted. Therefore, the DS18B20 is more reliable. Additionally, the whole sensor and its wires are waterproof, so compared to the exposed pins that Microchip has, the sensors are water and thus corruption resistant.

The advantages of the Microchip are the higher accuracy and the cheaper price. However, since our temperature sensors have to be immersed in fluid and it is harder to replace the components, we value the reliability more than the 0.25 degree accuracy. Also, the difference between \$ and \$ is not significant for this study. In the end, we chose to use the DS18B20.

Method to place the sensors

We explored four methods to place the sensors on our pipe.

- 1. Directly drill holes into the pipe and put the sensors inside, using an adhesive to glue the sensor to the wall of the pipe. Afterwards seal the holes.** This method is very accurate. However, it is very hard to replace any sensors if they are broken, or if the placement is not correct.
- 2. Stick the temperature sensors outside the pipe.** This is the easiest method to implement. However, the issue with this method is that the location of the sensors dramatically reduces their accuracy due to not being insulated from the external environment.

3. **Use a T junction to connect to the pipes, and then put the sensor through the T junction.** This way is quite easy to implement, as well, but the problem is that the pressure inside the pipe will be changed by the T junction.

4. **Put the sensors into modules and insert the modules into the system.** In this method, the problem is that we need to design the module. However, we can put the sensor into the fluid, which is more accurate. Also, once we have the module ready, we can insert the module into any place in the system, therefore it will be easy to test various locations.

In the end, we chose to use the option D because it is fairly accurate and because it allows the sensors to be easily replaced.

Below are the CAD drawings for the placement of the temperature sensor DS18B20.

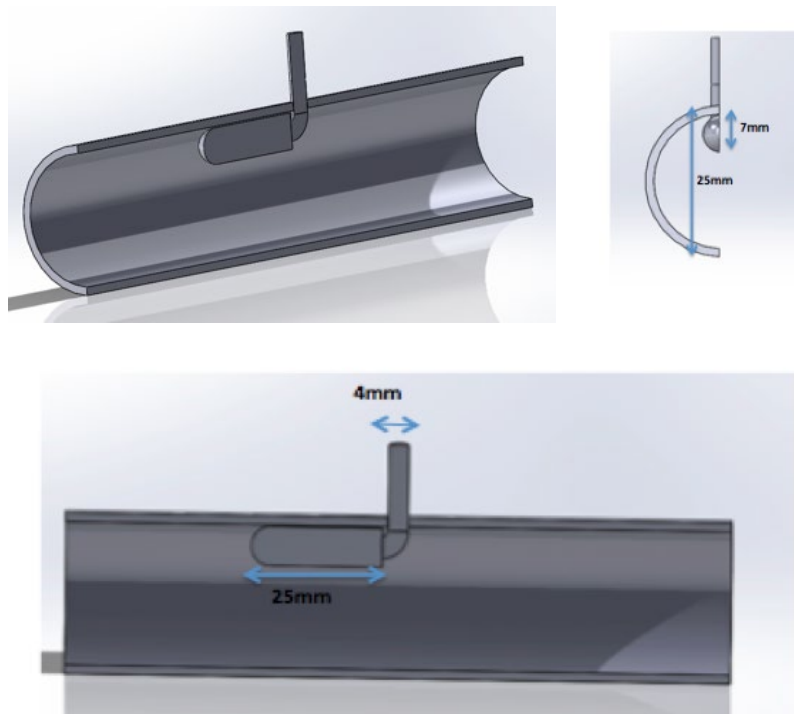


Figure A1: the CAD drawings for a sensor module. a) the cross-section picture with the 7mm sensor and the module. b) the side view of how to put the sensor in.

For this 100 mm long module, we can put the sensor into the module first, drill a hole that is 4 mm in diameter and then put the wire through the hole. Then, we can move the module around and connect it to the pipes.

Locations of the sensors

We want to test the temperature at different locations so we can verify the temperature drop and the heat transfer.

The locations of the sensors are shown in Figure A2.

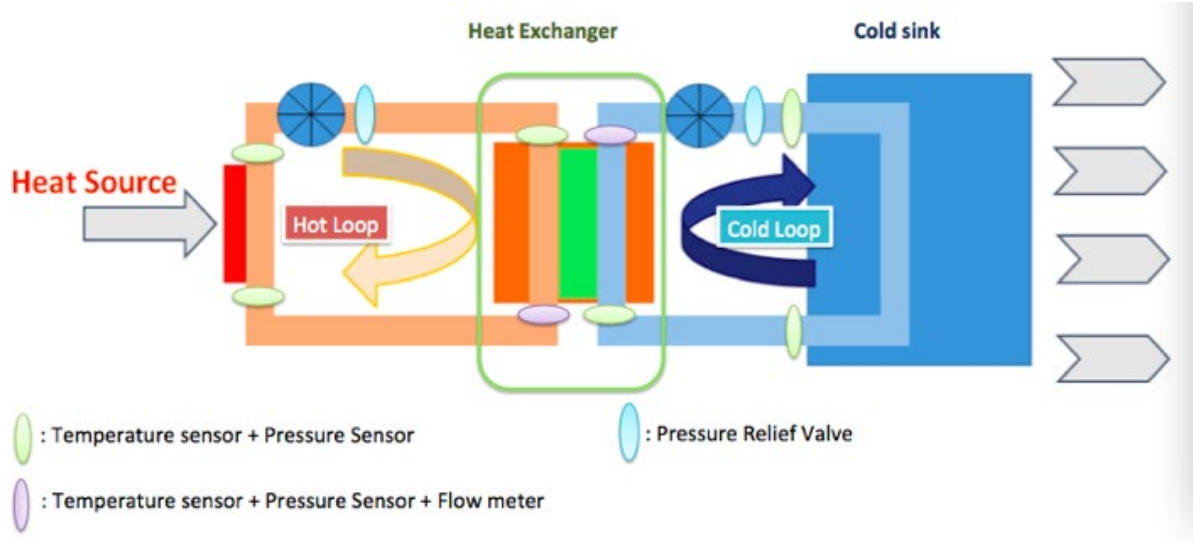


Figure A2: The locations of the sensors

We need one temperature sensor on both the heat source and the inlets/outlets of the heat exchanger so we know the temperature drop through the pipes. Also, we want to measure the flow rate at the exits of the heat exchanger, which is needed for the calculation of the heat transferred.

The pressure relief valves are placed in each loop in order to prevent a build-up of pressure, which could occur if there is an unexpected phase change. This situation may occur if the hot loop is overheated. The pressure sensors are placed in each loop in order to monitor the pressure for this very purpose.

c. Calculations and explanations of the capillary wicks

We consider a simple counter flow heat exchanger-thermoelectric generator system. The system generally consists of thermoelectric material placed between two conducting plates with warm flow on one side and cold flow on the other side. The goal is to determine what pressure would have to be supplied - by the capillary wicks or pump - and what pipe diameter is necessary to reach a given power output from the thermoelectric material.

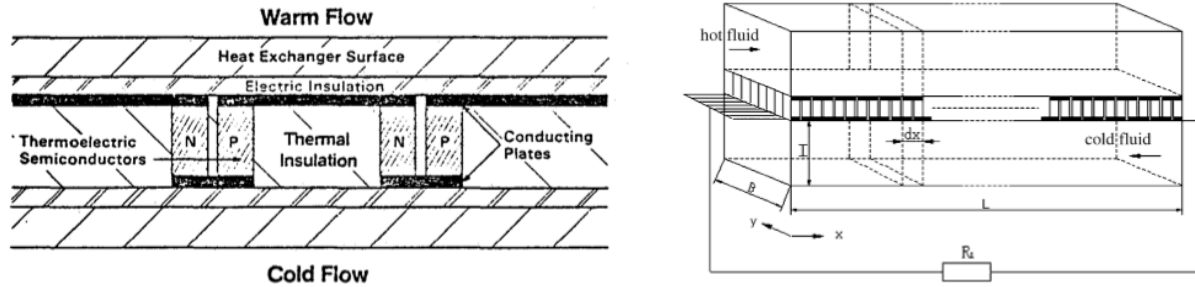


Figure A3: An overview of the heat exchanger-thermoelectric generator system.

The volumetric flow rate that can be provided by the capillary wicks is given by Darcy's law for a single-phase flow :

$$Q = \frac{kA}{\mu} \cdot \frac{\Delta P_c}{L}$$

where k is the permeability of the medium, A is the cross-sectional area of the capillary surface, μ is the dynamic viscosity of the fluid, ΔP_c is the capillary pressure induce by the medium, and L is the length traversed by the fluid through the medium.

For the capillary wicks, the approximate capillary pressure is given by:

$$\Delta P_c = \frac{2\sigma \cos \theta}{r}$$

where σ is the surface tension of the fluid, r is the pore radius of the medium, and θ is the angle of contact of the fluid in the pores.

For the capillary wicks supplied by 1-ACT, the pore size is approximately $r = 1.4 \mu\text{m}$. With the surface tension of water being $\sigma = 72.8 \times 10^{-3} \text{ N/m}$. This gives a capillary pressure of $1.04 \times 10^5 \text{ Pa}$, or about 15 psi.

Our assumptions on the capillary material are as follows: $L = 0.3 \text{ m}$, $\text{OD} = 2.54 \text{ cm}$. The wicks have a specified permeability of $k = 2.0 \times 10^{-14} \text{ m}^2$. The dynamic viscosity of water is $\mu = 0.282 \times 10^{-3} \text{ Pa} \cdot \text{s}$. The cross-sectional area of the capillary material is the entire surface area of the wick, since the fluid flows from outside the wick to inside the wick. Thus, $A = \pi \text{OD} \cdot L = 0.2390 \text{ m}$. Then the induced volumetric flow rate is $Q = 1.4709 \times 10^{-5} \text{ m}^3/\text{s}$ and the mass flow rate is $dm/dt = 0.0417 \text{ kg/s}$.

In the literature, we have found that mass flow rates of around 0.0660 kg/s at temperatures of 32 C at the heat sink and 140 C at the heat source yield efficiencies near 5%. Our computed mass

flow is close to 0.0660 kg/s. Furthermore, our temperature differential is shifted downward from the given temperature range in the literature, so the efficiency will theoretically be better. However, there are no numerical studies we can find that have results for our specific temperature range.

d. TEG Datasheet

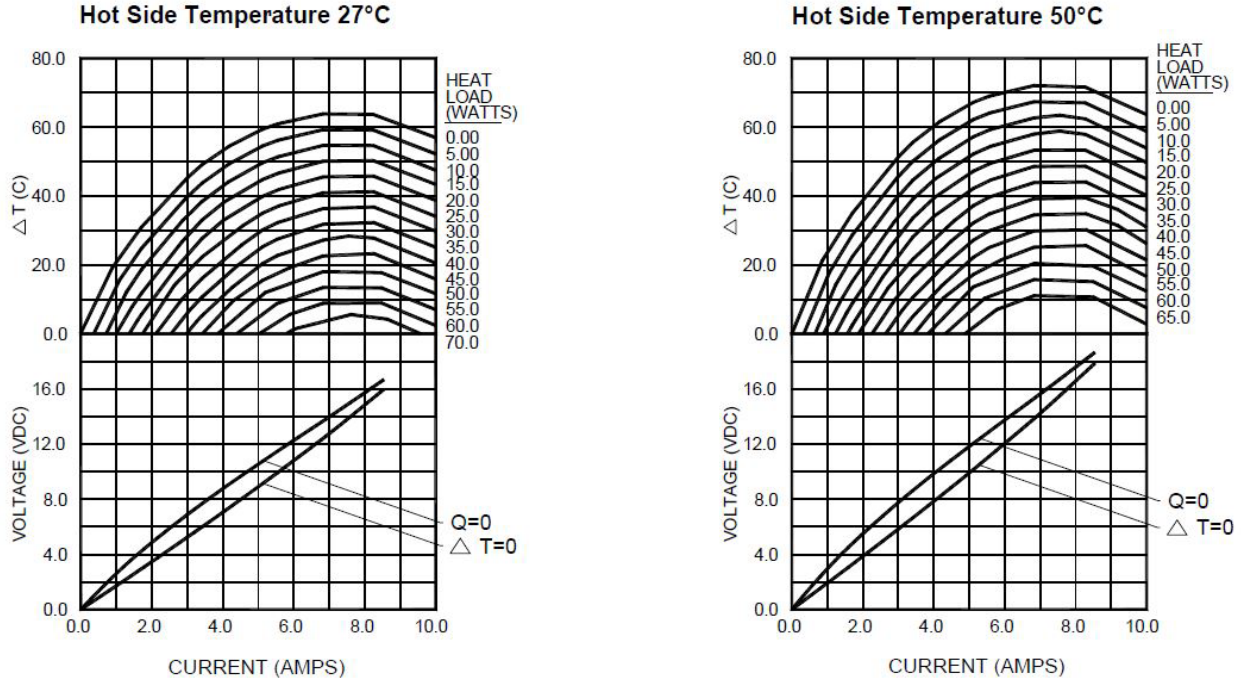


Figure A4: The spec sheet for the TEG module (Marlow RC12-8). In order to deliver the appropriate current for the TEG module to cool the working fluid we calculate the average heat transfer of the heat exchanger that we equate with the heat load, and calculate the necessary temperature difference.

e. Equation for Heat Transfer across Cold and Hot Pipes

$$\dot{Q} = A_{\text{total}} \frac{(T_{c,\text{in}} - T_{c,\text{out}}) + (T_{h,\text{in}} - T_{h,\text{out}})}{\ln \left(\frac{T_{c,\text{in}} - T_{h,\text{out}}}{T_{c,\text{out}} - T_{h,\text{in}}} \right)} \cdot \frac{1}{\frac{4x_{\text{pipe}}}{k_s A_s} + \frac{4x_{\text{TEG}}}{k_{\text{TEG}} A_{\text{TEG}}}}$$

$$Q_{\text{hot}} = \dot{m}_{\text{hot}} c_p \Delta T_{\text{hot}}$$

$$Q_{\text{cold}} = \dot{m}_{\text{cold}} c_p \Delta T_{\text{cold}}$$

Equation A1: The equations used to calculate the heat transfer per unit time [6]

In Equation A1, Q represents the heat, $\dot{Q}$ refers to the rate of heat flow, $T_{c,\text{in}}$, $T_{c,\text{out}}$, $T_{h,\text{in}}$, $T_{h,\text{out}}$ refer to the inlet and outlet temperature of the cold pipe, and the inlet and outlet temperature of

the hot pipe respectively. x_{pipe} , x_{TEG} refer to the horizontal distance along the pipe and the TEG material, A_{TEG} and A_s is the area of the TEG and the area of the TEG and the cross-sectional area of the pipe. $\dot{m}$ is the mass flow rate and c is the specific heat.[7]

f. Maximum Power Point Tracker

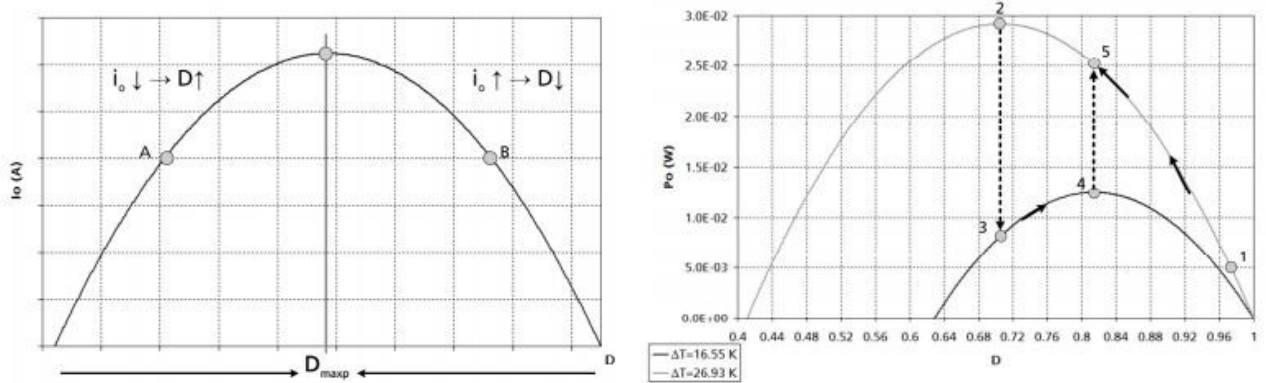


Figure A5: If the output current is increasing due to an increase in voltage generated from the TEG, the duty cycle must decrease, and vice versa, in order to reach a point of maximum output current (left). If the temperature gradient changes, the output power characteristics of the TEG changes and the duty cycle of the PWM signal going to the boost/buck converter must change accordingly. In this case, we lower the duty cycle to go from point 1 to 2 and then the temperature gradient lowers, which causes point 3 to be at a non-optimal duty cycle. This causes the duty cycle to increase, and we go to point 4 where we find our new optimal power output (right). [8]

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