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University of Idaho Facilities Department,

The following document is the final report on the Flue Gas Waste Heat Recovery project that was sponsored by the University of Idaho Facilities Department. The Fire & Ice Energy Recovery Team would like to thank the Facilities Department and Scott Smith for their support on this senior design project. This project has been instrumental in helping us reach our goal of graduating and becoming engineers.

Sincerely,
The Fire & Ice Energy Recovery Team

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Waste Heat Energy Recovery

By The

Fire & Ice

Energy Recovery Team

Brandon Nafsinger Scott McMurdie Garrett Oman and Bryan Perkins

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Flue Gas Energy Recovery

Team: Fire and Ice

Executive Summary

The Fire & Ice Energy recovery team set out to design a modular system that uses thermal electric generators to recover waste heat and convert it into usable power. This design was created for recovering waste heat from the side of the boiler in the University of Idaho steam plant.

This design need to be able to withstand the high operating temperatures found in the steam plant. The generator is required to be able to operate with little maintenance for an extended period. The system also must be modular and portable, which make it adaptable to other situations. The project had a modest budget of around $2500. Most importantly the system must produce useable power.

The system developed meets all the design requirements. The system consists of six identical modules wired in parallel. Each module is made up of 4 thermal electric generators (TEGs) wired in series, a steel back plate, a heat sink and a fan. The output of the system is routed to a handheld radio charging station where the power produced is stored in the radio batteries then used by the radio.

Upon completion, the system puts out 48 Watts of useable power. This power comes completely from waste heat and after the initial cost of production is free power.

Background

The steam plant at the University of Idaho uses several large wood fired boilers to create the steam used on campus for all the campuses heating and cooling applications. As you walk in the steam plant you immediately notice a large amount of heat radiating off these boilers, so much so that the ambient temperature next to the boilers reaches 55 degrees C. All this heat coming off the boiler is waste heat; it is just transferred into the ambient air and flows out of the plant in the air. The steam plant managers along with the engineering department at University of Idaho posed the question as to whether this heat, which is just a form of energy, could be transformed and stored as useful energy. This question led to an opportunity for the Fire & Ice design team to explore the possibilities of capturing energy from waste heat as a senior design project.

If the design team were successful at capturing and using the waste heat, there would be many benefits for everyone involved. The Steam Plant would have a new source of power and would be operating more efficiently. The design team will have completed a challenging and rewarding capstone project before graduating. Future students will be able to take the design and work from this project and possibly advance the design to create even more useable energy.

Problem Definition

Design Goals:

- Attain the largest ΔT across the TEGs
- Should be a module design that can be multiplied
- Minimize impact on existing structure or surfaces it is applied to
- Operates with little to no annual maintenance

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- Apply to surfaces with steady state temperature
- Find the optimal way to get the cold side cold

Deliverables:

- Team Portfolio: A collection of notes, datasheets, minutes and other documents that have been made and collected for this project.
- Logbooks: Our personal notes and research created over the entirety of the project.
- Poster Board: Shows a general overview of the entire project in an easy to read and understandable format.
- Final Design Report: A detailed paper created to convey the process and information gathered in the portfolio. The report will teach the reader how the team went about this project
- Hardware Prototype: A physical product that has been created over the course of the project timeline.
- 6 Modules, each consisting of;
    - 4 TEGs
    - 1 pin fin heat sink
    - 1 electric fan
    - 1 Steel plate for mounting
- 1 radio charger
- The assembly and wiring of modules in the steam plant

From these Design goals and Deliverables, out team was able to create a plan to have all modules installed on the steam plant and charging radios by the end of spring semester.

Project Plan

Tasks and Schedule:

This project was full of tasks to accomplish; with the goal of completing 6 modules that would be installed in the steam plant to charge two way radios about mid way though the first semester our team had a good idea of what needed to be accomplished.

Our team started with project learning for several weeks, and then moved on to decided where the TEGs would be mounted at the steam plant and what the power produced would be used for. The MEs on the project had to do all of the thermal modeling, assemble and design of the modules. The EEs on the project did the bulk of the testing, final installation and wiring of the modules in the steam plant. In the appendices section project timelines the first couple timeline are what where put together thought as our plan throughout the year showing what we wanted to accomplish and when. The next page the project plan shows the actual time it got done.

The timelines show that everything we planed was completed be usually 1 to 3 weeks delayed. After working in the industry as an intern at SEL this is pretty standard to set a plan and have it pushed out. It is always better to do things correct and complete than to get it exactly done on time.

Team Responsibilities:

Our team consisted of two mechanical engineers and two electrical engineers with duties as follows:

- Finances (Brandon Nafsinger): In charge of making the bill of materials.
- Primary Client Contact (Scott McMurdie and Brandon Nafsinger): Primary contacts for our client, updating them on progress and addressing the needs and questions the client may have.

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- Team Organizer (Scott McMurdie and Brandon Nafsinger): Organizes meetings among team members and maintains all communications in order to ensure everyone is doing their part.
- Team Documenter (Bryan Perkins): Records minutes of each meeting held, documenting any and all updates and information during them.
- Reflector (Garrett Omen): Directs brainstorming of ideas and points the team in the correct direction to maintain progress of the project at hand.

While duties were assigned and generally maintained, there was a sharing of some duties which occurred. All of our meetings involved the client; so he was regularly updated on how the project was going. Also when ordering parts our team went directly through our client because he was always at our meeting and he wanted ordering to go through him.

Concepts Considered

Client Interview

With the start of the project, our team turned to our client and professors, and asked them about their desires for the project. While there was a previous senior design team who had been working with TEGs our instructors did not give our team any of their work because they wanted us to be innovative and not go down the same path they did. Having the perspective of the client was important in kick starting our work. For this, we developed a list of questions, specifics on the project such as desired components and results. Since we were starting this project from scratch most of the questions came after project learning was completed. Our client interview turned out to be informal because our client attended all our meetings and was also our mentor. All our questions were to pick the client's brain and see his vision. Having his input allowed us to better visualize the expectations and what to look for when proceeding with the project.

The numerous meetings were productive, allowing us to have a solid foundation upon which we could begin to move forward. There was still plenty to figure out but the concept of the project and the desired result were made clear enough. The main goals of the project were revealed at this point, allowing a good point from which the project could start.

Concept Development

Starting this project from scratch turned out to have many challenges. First came project learning, the biggest thing we had to do research on was how a TEG worked. It is a pretty complicated process and it is just easier to think of it as a magic black box that requires a temperature difference to generate electricity. There were many other concepts that where study during the project learning to include radio chargers, heat sinks, and fans effects on heat sinks. Once the project learning was over modeling of our design and testing was to commence.

The MEs on the team started with attempting to model they system from examples in there heat transfer textbook. The modeling was difficult because there where so many unknown factors. With all the unknown, a lot of guesses had to be made making the models less accurate. Being unsure of the results of the models our team did some digging and found some of the TEGs the previous year's senior design team had used and started doing some testing.

The initial testing provided our team with some much-needed information and proof of concept. During this initial test, we found that compression of the TEGs is very important. The TEGs are coated with graphite sheets and surfaces that they sit on are not perfectly smooth. With compression, the graphite sheets fill in the micro structures and allow for convection to

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be more efficient. The next most important concept we learned from testing was that the hotter we could operate the TEGs at, even using the same cooling method for the cold side, the more power would be generated. This is due to ambient air staying the same temperature, which helps increase the temperature difference across the TEGs as the hot side temperature rises.

Snapshot 1

The first Snapshot Day had each group set up a poster board explaining plans and expectations of the project, as well as any ideas and progress we had made. The poster board our team created covered several concepts:

- An abstract/problem statement for the project and design goals
- Specifications from our client for the final product
- Project learning or TEGs
- Heat transfer equations
- Graph of Temperature difference vs Power output of proposed TEGs
- A Gantt chart detailing our expected timeline for the spring semester

While it was not perfect, it was a good start. We received some level of feedback from peers, most expressing interest in how the project makes power from heat. There were a lot of people who stopped by our booth with many different ideas that helped in the production of our final design.

Design Review 1

Around the end of the semester, the first design review took place. Our client as well as the course instructor and about ten other people from facilities attended and offered critique to the presentation our team gave. This presentation covered much of the same details as the Snapshot, only with further detail provided on our progress and any developments on the project. Thus, we covered the specifications and vision of the project.

What we came away from during this review was a need to act and make some decisions for the project. Our goal going into this design review was to give our client several options on how to build our module. We were not getting the results we need from modeling our design so we wanted to buy the parts and build a prototype to figure out some of our unknowns. Our team presented several options but at the end, we failed to conclude and have the client make a final decision. We had some difficulties with this first review but reconciled it before the semester was over. After not completing the goal we set out to accomplish at the design review. We set out to reconcile our mistakes before the end of the first semester. We created a detailed list of the entire component we wanted and submitted it to the client for review. By the end of the semester we had all the parts on order we need for testing to begin first thing the following semester.

Snapshot 2

The 2nd Snapshot Day was right after the first design review. Our poster consisted of mostly what we present at the review;

- Design goals
- Testing with prior teams TEGs
- Gantt chart showing our timeline to finish project the next semester

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- Heat transfer equations
- A module render in solid works
- The heat sink and radio charger description
- Predicted output power of our module base on different Delta T

At point we were still getting our parts list together to be approved by our client to perform testing since our models had to many unknowns and guesses making them incorrect.

Design Review 2

By the time the spring semester came around, it was time for another design review to pick up where things left off as well as leave a better impression than the previous time. This design review was pushed of about a month from when it was supposed to be completed because at end of the fall semester through winter break some issues arose with ordering the parts we need to complete testing. The team put in the time to make this design review go smoothly and show our client and instructors that we had a handle on the project.

After all the parts had been received, it was time to build our test module. There were many things to consider for this test module. We need to figure out how we were going to get the hot side, how everything was going to be mounted, how we were going to take measurements and how everything was going to be hooked together?

A hot plate could barrowed from the physics department, and thermocouple and meters where supplied by JJ in the ECE department. The MEs created several different mounting designs and thought trial and error where able to produce the simplest, most effective design.

After completing enough testing, we were ready to present the second design review and explain to our client and professors the direction this project needed to go, to be completed on time. Everyone was very happy with the results of the second design review and we were on our way to completing the project.

Snapshot 3

A final Snapshot was held around the same time as the 2nd design review, covering much of the same ideas. This time we took our new research and testing data and included;

- Testing results with natural convection
- Test setup picture
- Gantt chart to show how we were going to land the project
- Manufacturing picture of module preloading
- Bill of materials arrange by deliverables
- Wiring diagram for final product in steam plant

We were very close to accomplishing our project at this point, or so we thought. We had everything order that we need but though the test prior to this snapshot and 2nd design review we proved that natural convection would not work and our milled-out plate design with 5 holes tapped into the heat sink was not performing as it should. We still had a lot of work ahead us to land this project.

Developmental Obstacles

It would be no exaggeration if most this project was spent overcoming obstacles, primarily one key issue which was achieving the compression required for TEGs. Our team went thought several iterations for a mounting plate to include: a completely milled out plate with TEGs on the boiler itself, partially milled

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out plate with 5 holes, tapping out the aluminum heat sink and different iterations of hole patterns. After a lot of complex designs and learning what would be best our team decided to dramatically simply our plate design. We ended up going with a flat steel plate with holes drill and bolts counter sunk, 9 through holes drilled into the heat sink, with each hole only removing only one pin, and lock washers and steel bolts to mount everything together into a single module. This was the biggest obstacle our team encountered in this project but eventual we overcame and design the best product.

Concept Selection

When making product selections for our final design there where many aspects that went in to our final decisions. The parts we used for our final design are as follows:

Fan: Traditionally, in a computer, air is pulled thought the heat sink and pushed out a case. This is because all the hot air needs to be away from components. Through testing, it was found to be more efficient to push air down through the heat sink. Our design has no need to push the hot air away from the modules because they are not surrounded by a case. Pushing air through the heat sink creates a turbulent boundary layer that causes more heat to be disputed from the heat sink. Velocity is much more important than CFM which is why we choose the Panaflo Case Cooling Fan because it had highest velocity to power consumed.

Heat sink: When it came to picking the heat sink to cool the TEGs we choose a 5x5x2.5" pin fin because they provide the most surface are making them the most efficient style of heat sink . Next we choose a flared configuration verses the sparse because it give room between each fin give more space for convection. The next consideration was metal type, so our group went with aluminum because it is inexpensive and an excellent conductor of heat.

TEGs: The TEGs where chosen because they had the highest output for our operating temperatures and where some of the only one found that could even operate continuously at the temperatures at the steam plant.

The Plate: When it came to design and manufacturing the mounting plate that would hold everything together we went through numerous different designs. The first design we attempted was a five hole with milled out pockets and holes taped into the heat sink. The thought was milling out the still would keep the TEGs in place and the file holes would give compression across each of the TEGs from either side and with the holes taped into the heat sink there would be no fin loss by drilling all the way through. There ended up being several issues with this design to include large bending moments on the bolts, stress concentration where the plate had been milled out, and an extremely complicated process of milling out the plate and drilling and tapping the heat sink. The threads that were tapped into the aluminum heat sink yielded when the module reach it operating temperate, due to thermal expansion of the aluminum and steel, causing the module to lose compression. The complex design made for long manufacturing times and excessive waste that really added no benefit to the design.
For the finally plate design our team took a step back and simplified the process. We changed to just a solid steel plate with no milling, a 9 hole bolt pattern, and a through bolt design though

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heat sink with lock washer and steel nuts. This simplification of the mounting plate made the manufacturing quicker and easier.

The Radio Charger: The radio charger was chosen because it had a lot of functionality and protection. Some of the most important things about it are it accepts a large range of input voltages it easy to regulate the output voltage. It also can be a detection system by giving over and under voltage errors if something where to malfunction with the TEGs.

Fan driver voltage limiter: This voltage limiter is from the same company that manufactures the TEGs. It use is to get the system up and running and protect the fans from being damaged.

System Architecture

Manufacturing Plan

- **Making plate**
  - Drill 9 holes in the plate with a diameter of 0.125”. See drawing for specific distances
  - In the same places drill 9 counter bore holes with a diameter of 0.185” and a depth of 0.125” (these counter bore holes are to fit the head of the bolt in the plate)
  - Drill 2 holes for the fan mounting threaded rods with diameter of 0.25” (these holes with be threaded with a ¼ - 20 tap.
  - Mill out slots for the mounting bolts. In order to provide error in installation the size of the slots will be 5/16” and the mounting bolts will be 1/4”. The center of the bolt hole will be 0.5” for the edge.
    - See drill charts for specific bits and taps used for manufacturing
    - Reference drawing for specific dimension of holes
- **Heat sink**
  - Using the same pattern for the Heat sink as was used for the plate, drill 9 holes with a diameter of 0.125” through the heat sink. Ensure that the heat sink is secured with top clam, 123 blocks and two cross members as shown below in figure 1.
- **Compression**
  - Compression is achieved by using a hydraulic press.
  - Thin aluminum cross members are used to stabilize the heat sink; they are place on the diagonals of the pin array. The height of the members are slightly higher than that of the pins, the thickness is slightly less than that of the pin separation.
  - On top of the heat sink the TEG are place as desired, then mounting plate in then placed on top.
  - Tighten down all bolts to hand tight before placing under hydraulic press
  - 4 1-2-3 blocks are used to allow space to tighten bolt while under compression
  - A think block of steel is used on top of the 1-2-3 blocks

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Final Product

Our team's final product puts all of our concept selections together in to one module. This module was meant to be able to be easily replicated, low maintenance and simple to install. The steel plate was incorporated into our design because it makes it easily to mount to any flat surface, bolt the heat sink over the TEG modules to provide compression and tap holes into threaded rod for fan mounting. Since the TEG modules require 4kN of compression our team switched from tapping out the heat sinks to a though bolt design with steel bolts, lock washers and nuts. This way of bolt everything together has several advantages: The steel bolts and nuts have a very high strength and will not yield as the module heats up and materials start to expand. So this can only increase compression on the TEGs aid in performance. The next advantage is that it makes our design portable and easy to install. Since everything is bolted together and compression of the TEGs has already been achieved. The module could be easily manufacture and then shipped to anyone and easily installed without any special equipment.

Project Potential

This project has great potential. It is taking waste heat that cannot be used any other way and turning it in to usable power. If more efficient thermoelectric materials where developed our system has a lot of great feature that could make this a viable options for many different industrial settings and power plants.

Design Evaluation

Design Failure Mode Effect Analysis (DFMEA)

One of the ways engineers analyze a design is using the DFMEA. For our project some of the potential failure modes include: TEG failure, fan failure, module damage, wiring damage and faults in the circuit. Many of the actions take do not reduce the Risk Priority Number RPN) because the only action to take is simply replacing the damaged or failed part. In two cases of potential failures we were able to come up with solutions that would reduce the RPN. In the case of fan failure, the fans just need to be cleaned on a regular schedule and that will reduce the RPN by half. The next case was faults in the system. By adding a breaker the RPN could be reduced by more than half of its original number. All of this date is displayed in a spread sheet in the appendices.

The Test Setup

Our test set consisted of a hot plate to simulate the boiler, clamps to hold the module to the hot plate, our module, thermocouple to measure the hot, cold and tip temperatures of the module and multimeters to read thermocouples, voltage and current coming from the module. Our test procedure was to get the plate up to steady state, were the hot side temperature is not changing. While the module is warming it we also were our startup procedure was tested for the electric fans. The fans start turning when the system reaches about 4 volts. This engages the fan drive voltage limiter and starts the fan. Once the system reaches steady state and the modules are output more voltage than the fan can accept the voltage limiter limits that fan to it rated 14 volts. At this point we take voltage and current measurement across a varied load and determine where max power is produced. These results are shown in the appendices.

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Green Engineering

The last evaluation of our product is taking the environment into consideration. There are no toxic or hazardous materials used in the design. The fabrication of the system requires only the electricity to run the machine shop. All of the waste from fabrication is solid and minimal. The system produces no waste through use during its lifetime. After the lifetime of the system only solid recyclables will be left.
In addition to these features this system captures waste heat and recycles it into useable energy. All in our entire project is extremely green and having only positive effects on the environment.

Future Work

Automatic Switch for Wiring Configurations

An automatic switch using either voltage or temperature needs to be added into the different wiring configurations show in the appendices for the wiring diagram. Since the wood boiler is not always operating at the same temperature due to demand during different season it will be necessary to change this once or twice a year. This would be a cheap addition and save some headache when trying to reconfigure the modules.

Propane fridge cooling system

The idea uses how a propane fridge works in a travel trailer. There is a closed loop system that through some chemical reactions between ammonia and nitrogen gas that create a cooling effect. The only energy source need to make this system work is heat to turn the ammonia into a gas, which the steam plant has plenty of extra heat. If this could somehow be incorporated into our system to have freezing temperatures is pumped into the fans this could up the output of each module by more than 4 times there output with just the fan. A prototype up this would be the cost of a propane refrigerate and the time to figure out how to get that cold to the modules. I think this is a viable senior design project and could make this system something that is cost effective and worth installing in power plants everywhere.

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Appendices

Calculations

EES model

Thermal Resistance of Heat sink

$$R_{\text{fin}} = \frac{T_b - T_f}{\dot{Q}_{\text{fin}}} = \left[1 + \frac{mL\,\phi}{Bi_c}\right]\left[\sqrt{hPkA}\,\phi\right]^{-1}$$

where:

$$\phi = \frac{mL \tanh mL + Bi_e}{mL + Bi_e \tanh mL}$$

and:

$$Bi_c = \frac{h_c L}{k}, \quad Bi_e = \frac{h_e L}{k}, \quad Bi = \frac{h t_e}{k} < 0.2$$

$$t_e = \frac{A}{P}, \quad mL = \sqrt{\frac{hP}{kA}}L$$

Inputs

- L – fin length
- A – cross sectional area of fins
- P – Fin perimeter
- k – Thermal conductivity of fin material
- h_c – Base contact resistance
- h – fin convection coeffiecient
- h_e – fin tip convection coefficient

Results

- R_fin – thermal resistance of Fins

IMPORTANT NOTE

R_fin was given for our heat sink was given as (0.57 W/K), these are the equation I used to determine the thermal resistance we would need to have in our heat sink. h and h_e are hard to calculate because they are dependent on the temperature distribution of the fin, which at the point I did these calculation was unknown, q was also not know at this point. The error in the EES model is most likely because I assumed R_fin = 0.57 W/K, this value is not a constant but varies with h.

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EES model

(CODE)

```
"CAPSTONE PROJECT"
"Thermoelectric Generators"

T_1 = converttemp(C,K,240) "Boiler Temperature"
T_amb = converttemp(C,K,23)  "Ambient Temp."
"T_2 = converttemp(C,K,165.7)"

R_tc_prime = 0.000005 [m^2-K/W]  "Contact Resistance"
W = 0.056 [m] "Width of TEG"
R_tc = R_tc_prime/W^2  "External resistance on TEGs"


{h_r = epsilon * sigma *(T_2+T_1)*(T_2^2+T_1^2) }"Radiation heat transfer coefficient"          "(1)"
epsilon = 0.9  "emissivity"
sigma = 0.000000056703 [W/m^2-K^4]

"Conduction resistance trhough one module"
N = 900 "Number of p-n semiconducting modules in all 4 TEGS"
L_TEG = 0.0025 [m] "Use half the distance of TEG"
A_cs = 0.00000256 [m^2] "Cross-sectional Area of each pellet"
k_TEG = 1.2 [W/m-K] "Thermal Conductivity of Bismuth-Telluride"
R_t_cond_mod = L_TEG/(N*A_cs*k_TEG) "Coduction resistance of one module"

"Heat transfer rate into device"
q_1 = (1/(R_t_cond_mod))*(T_1-T_2) + I*S_eff*T_1 - I^2*R_eff                "(2)"
S_eff = 0.1435 [V/K]  "Effiective Seeback Coefficient"
R_eff = 5.19 [ohms] "Internal resistance on TEG"

 "Heat transfer rate out of device"
q_2 = (1/(R_t_cond_mod))*(T_1-T_2) + I*S_eff*T_2 - I^2*R_eff                "(3)"

"Heat transer through external resistances (plate and TEG)"
q_1 = (T_alpha1 - T_1)/R_tc                                              "(4)"

"Heat transfer thought Heat sink"
R_rad_conv = 0.57 "Thermal Resistance of Heat think"
q_2 = (T_2 - T_amb)/R_rad_conv                                           "(5)"


I^2*R_eff = I*S_eff *(T_1-T_2) - 2*I^2*R_eff                               "(6)"

P_n = q_1 - q_2

P_n = I * V
```

Results

Unit Settings: SI C kPa kJ mass deg

A_{cs} = 0.00000256 [m^2]	ε = 0.9	I = 1.051 [amp]
k_{TEG} = 1.2 [W/m-K]	L_{TEG} = 0.0025 [m]	N = 900
P_n = 17.2 [W]	q_1 = 197.8 [W]	q_2 = 180.6 [W]
R_{eff} = 5.19 [Ωs]	$R_{rad,conv}$ = 0.57 [K/W]	R_{tc} = 0.001594 [K/W]
$\overline{R}_{tc'}$ = 0.000005 [m^2-K/W]	$R_{t,cond,mod}$ = 0.9042 [K/W]	σ = 5.670E-08 [W/m^2-K^4]
S_{eff} = 0.1435 [V/K]	T_1 = 513.2 [K] {240 [C]}	T_2 = 399.1 [K] {125.9 [C]}
T_{alpha1} = 513.5 [K]	T_{amb} = 296.2 [K] {23 [C]}	V = 16.37 [V]
W = 0.056 [m]		

No unit problems were detected.

Calculation time = 15 ms

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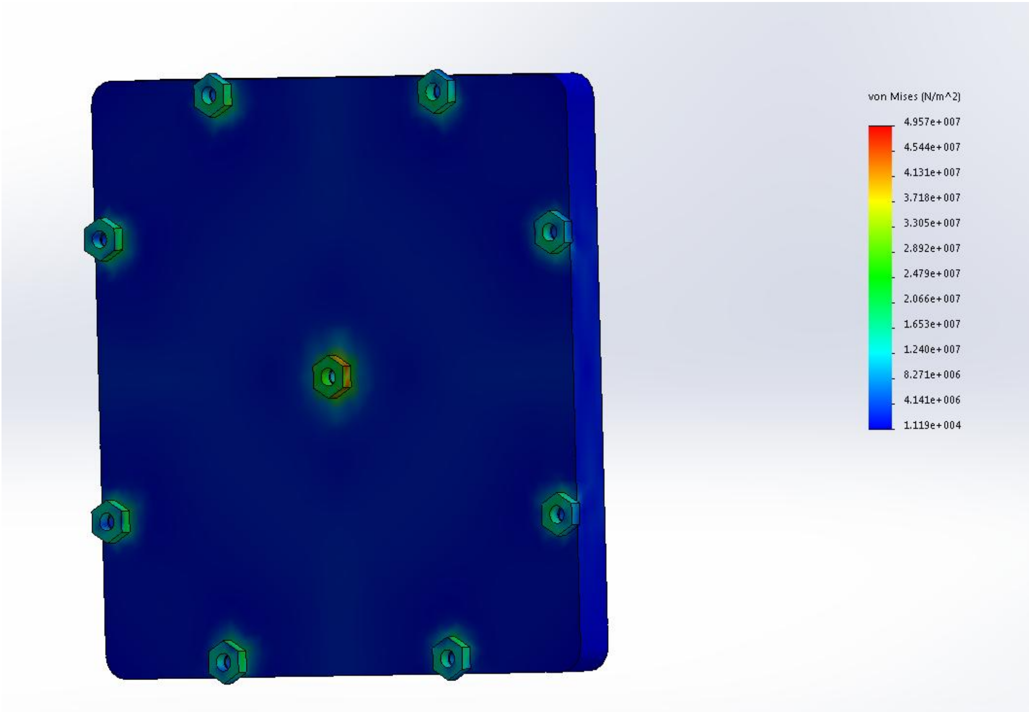
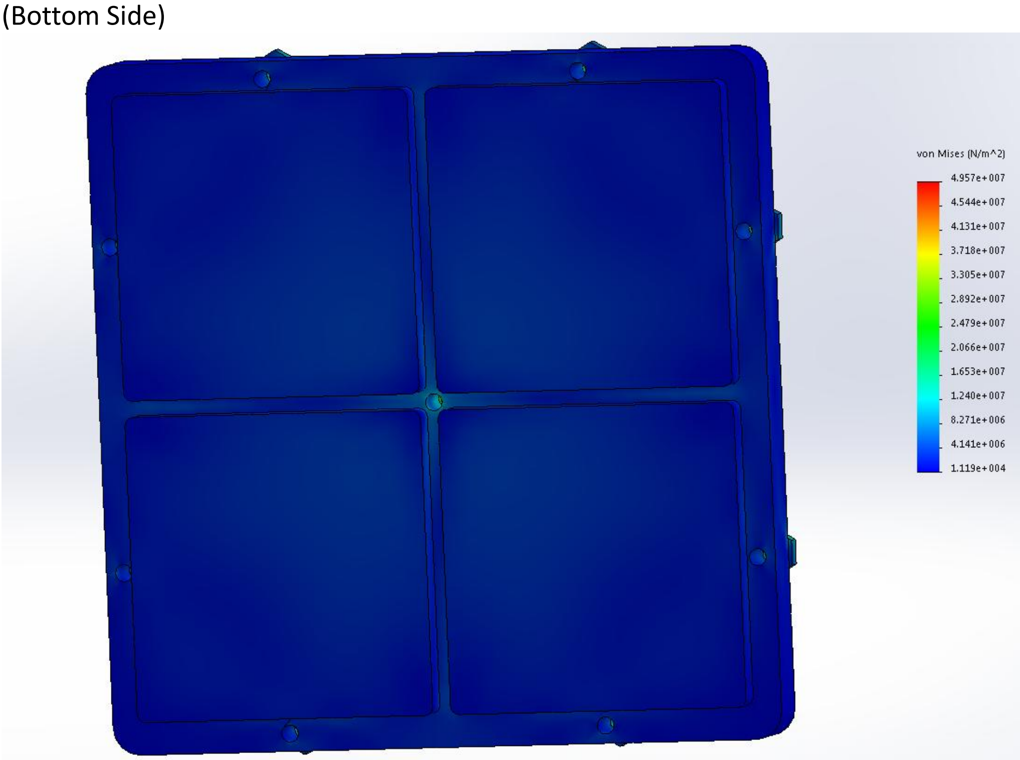
Stress Analysis on base of heat sink

(Top side)

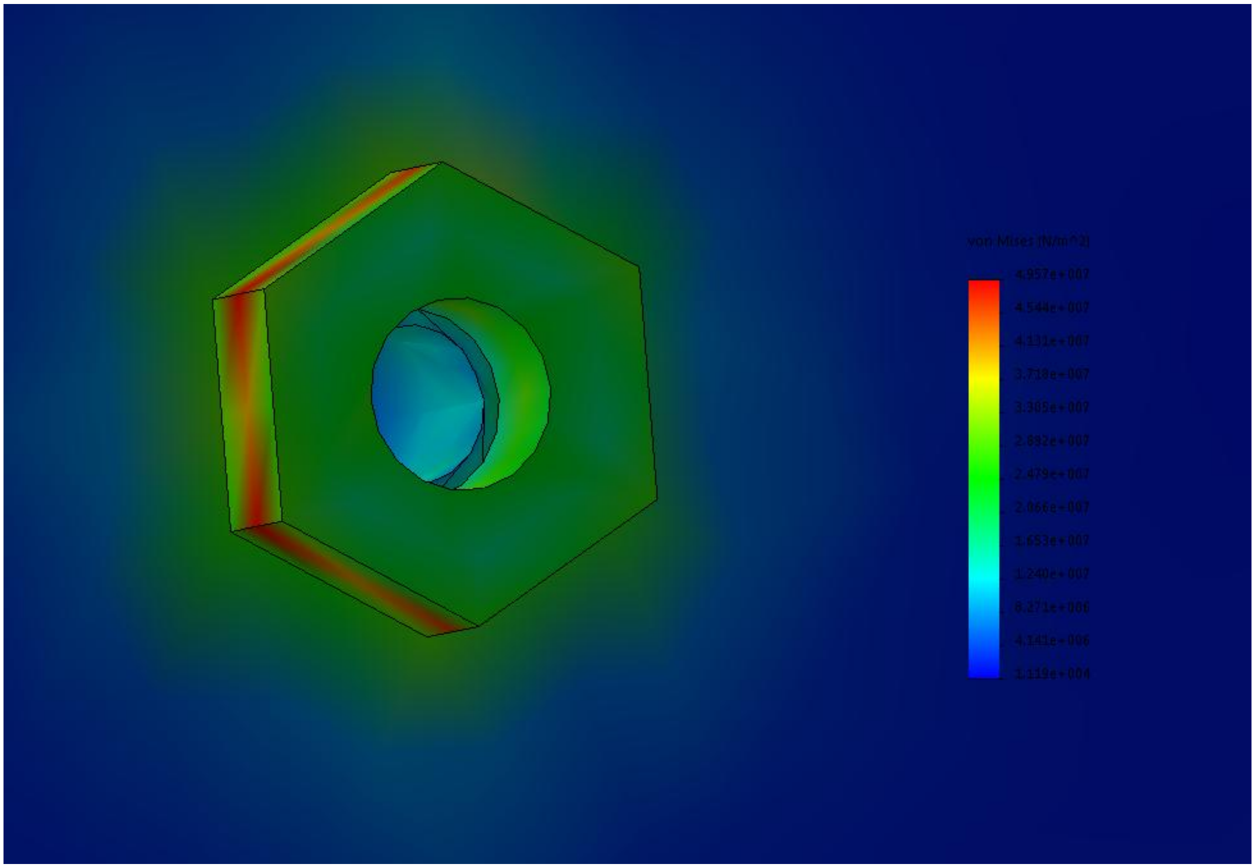


(Bottom Side)



(Close up)

`



Stress Analysis on plate

(Top view)

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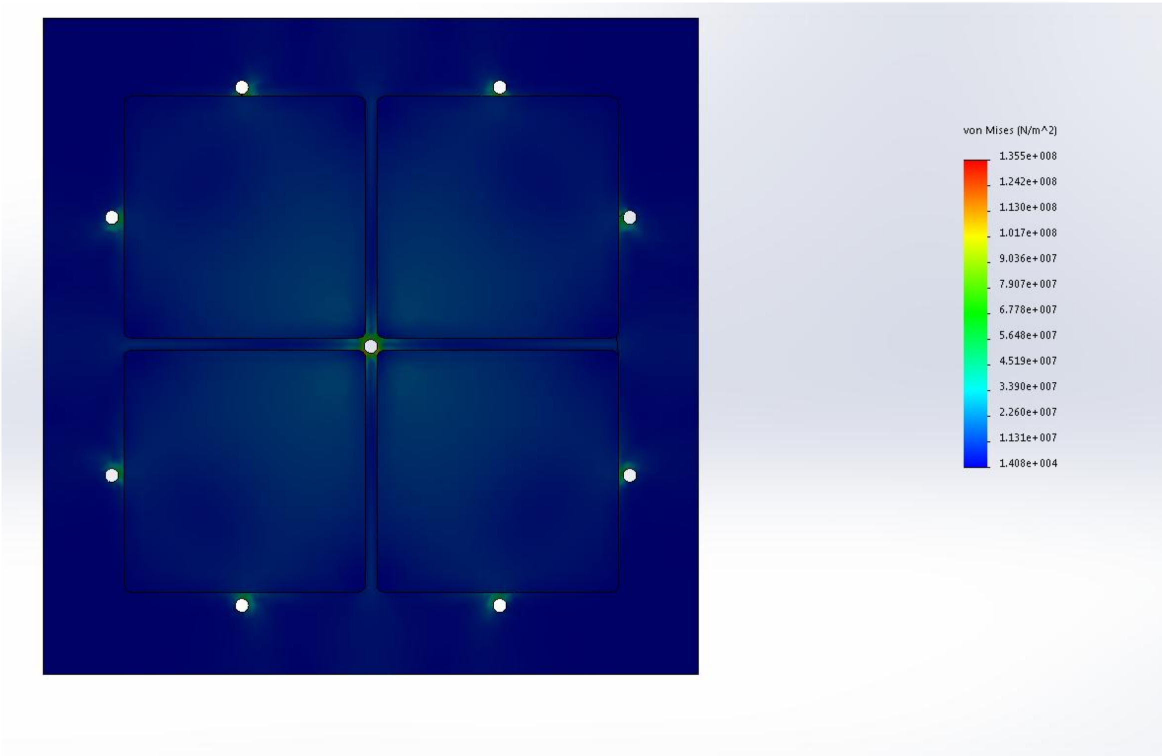
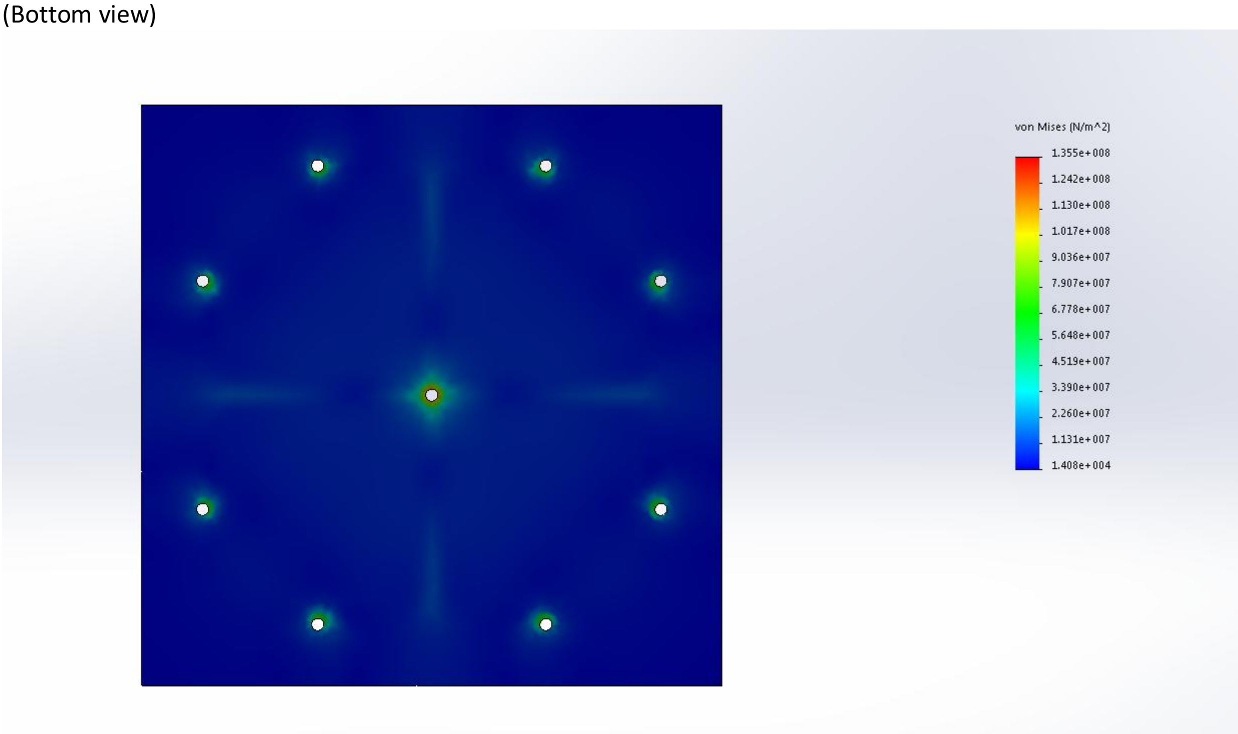


(Bottom view)



(Close up)

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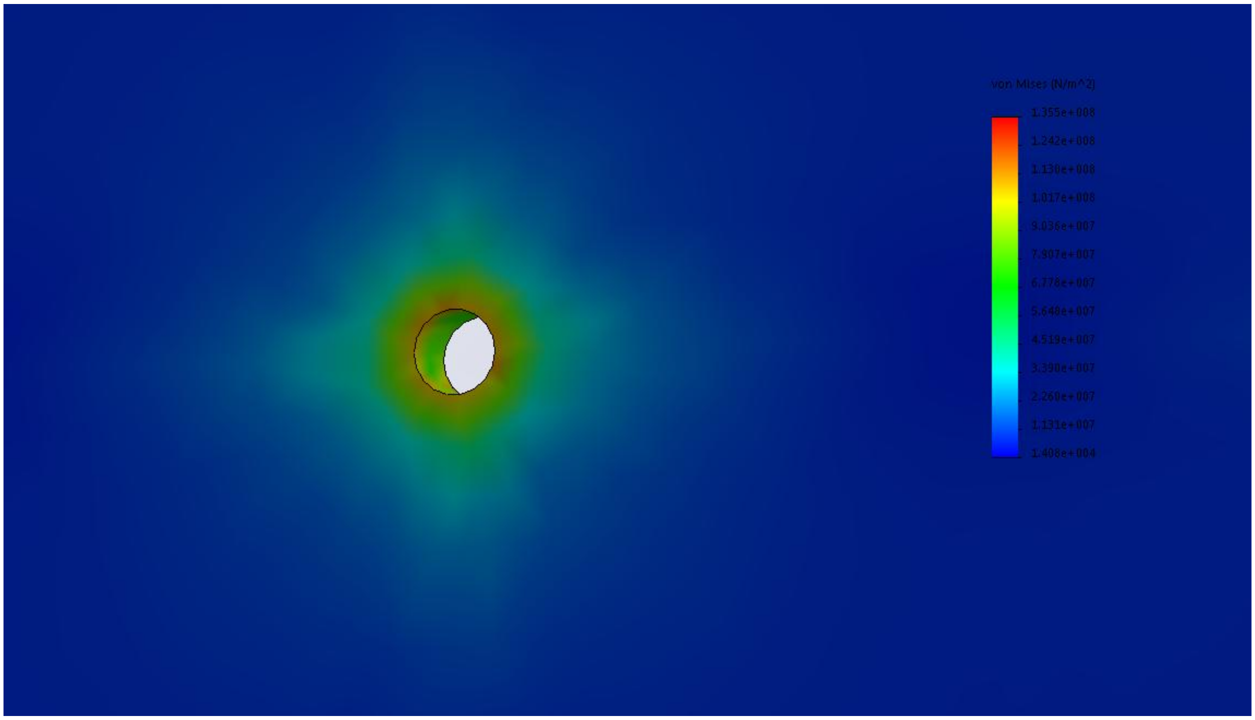

von Mises (N/m^2)
1.355e+008
1.242e+008
1.130e+008
1.017e+008
9.036e+007
7.907e+007
6.778e+007
5.648e+007
4.519e+007
3.390e+007
2.260e+007
1.131e+007
1.408e+004

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Electrical Transmission Calculations

Losses in power transmission

$l_w := 60 \cdot ft$ $I_{line} := 6 \cdot A$

At 122°F

6 Gage

$$V_{loss6} := \left(\frac{0.4416\Omega}{1000} \cdot 60\right) \cdot I_{line} = 0.159V$$

8 Gage

$$V_{loss8} := \left(\frac{0.7023\Omega}{1000} \cdot 60\right) \cdot I_{line} = 0.253V$$

10 Gage

$$V_{loss10} := \left(\frac{1.117\Omega}{1000} \cdot 60\right) \cdot I_{line} = 0.402V$$

12 Gage

$$V_{loss12} := \left(\frac{1.775\Omega}{1000} \cdot 60\right) \cdot I_{line} = 0.639V$$

14 Gage

$$V_{loss14} := \left(\frac{2.823\Omega}{1000} \cdot 60\right) \cdot I_{line} = 1.016V$$

Losses in transmitting temperature readings

$I_{temp} := 1mA$

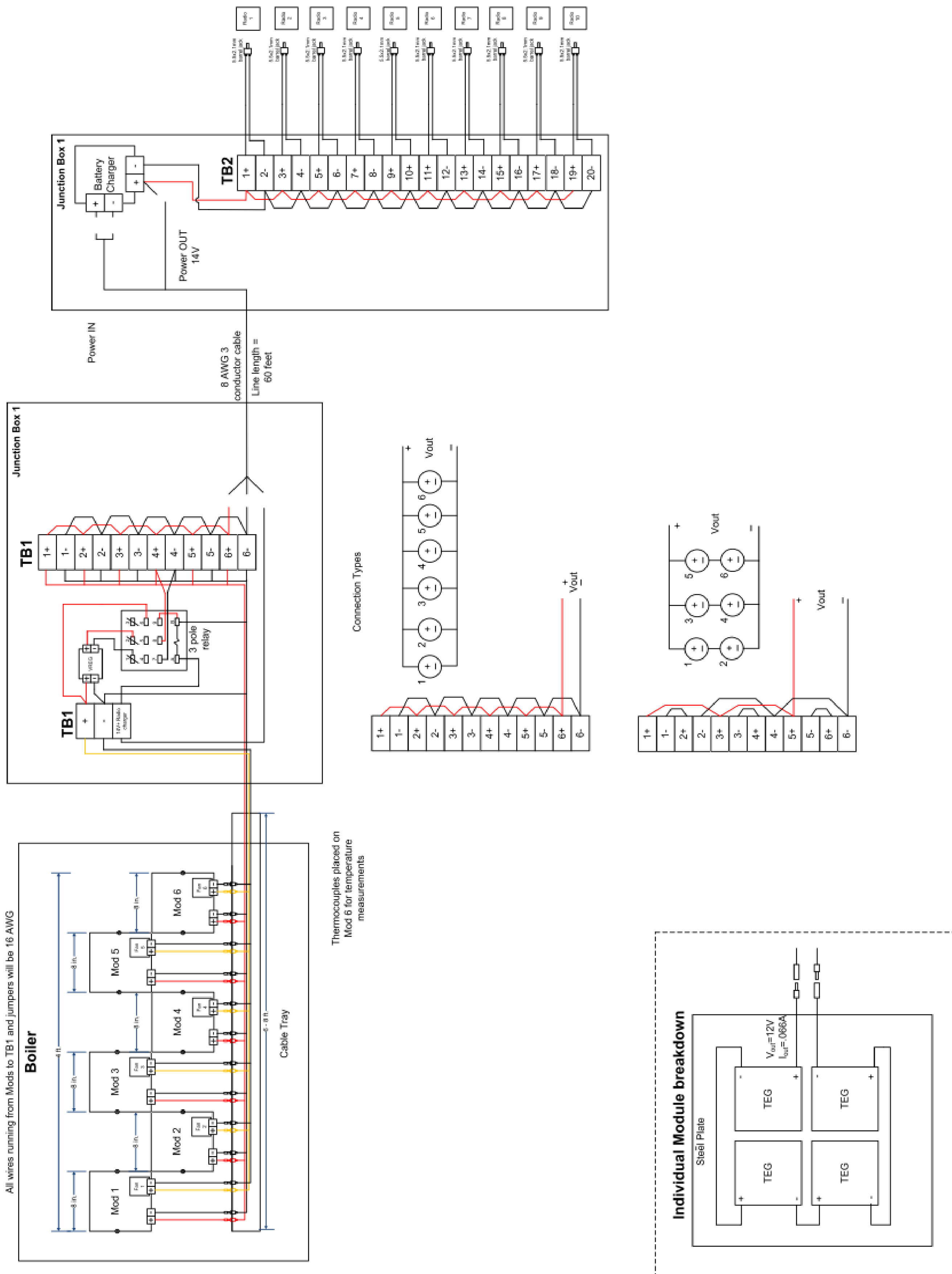
18 Gage

$$V_{loss18} := \left(\frac{7.138\Omega}{1000} \cdot 60\right) \cdot I_{temp} = 0.428mV$$

`

Drawings

Electrical Schematic



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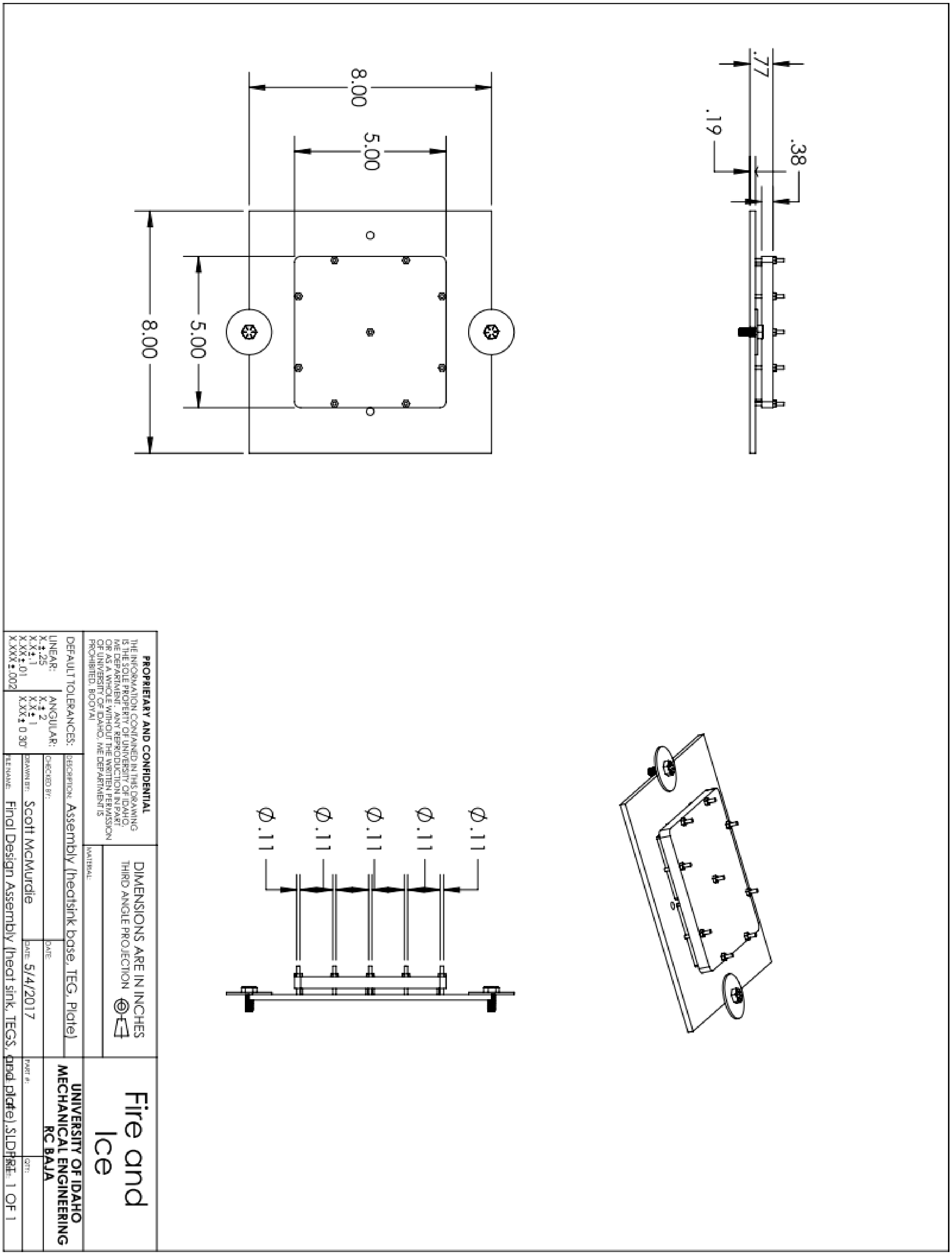
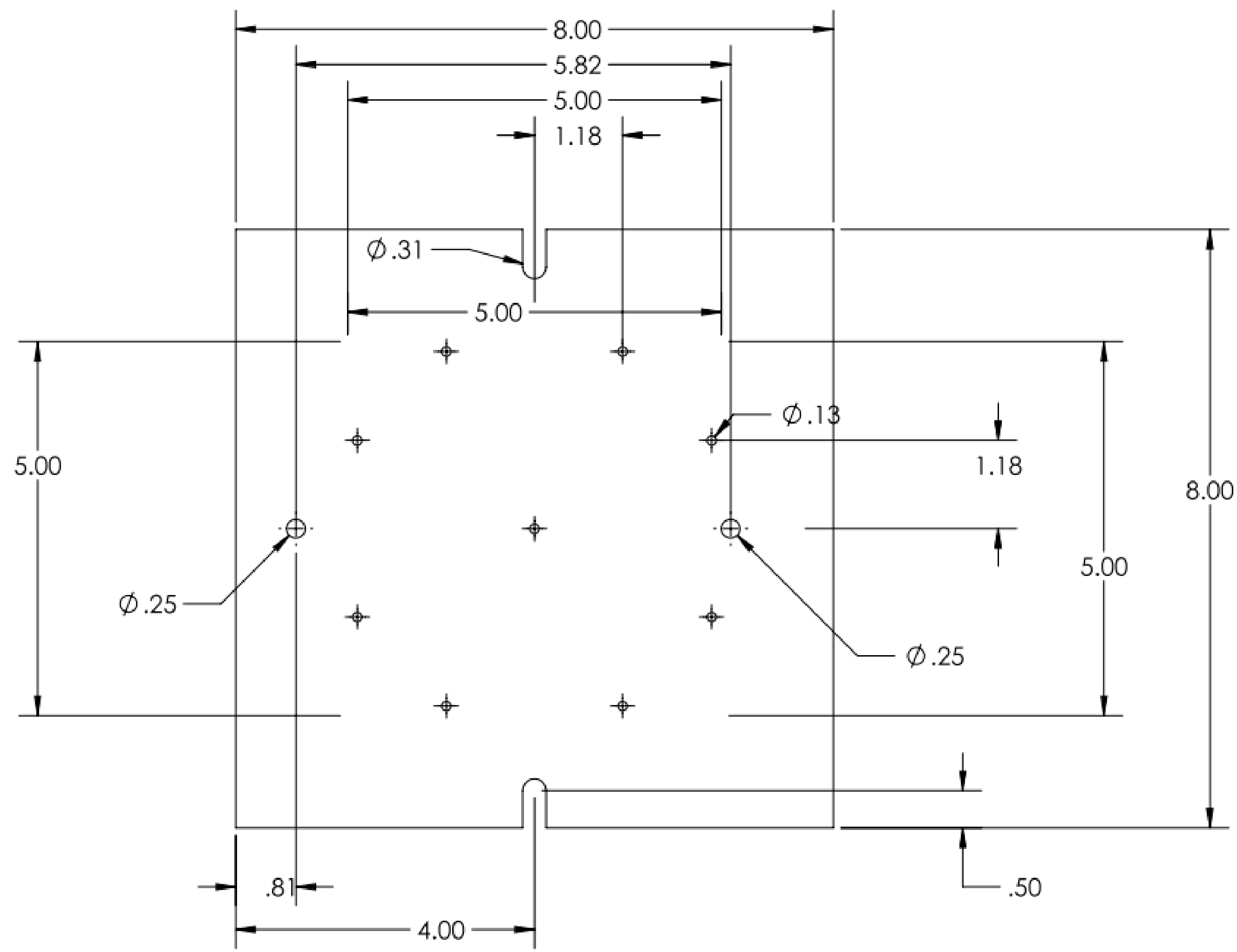
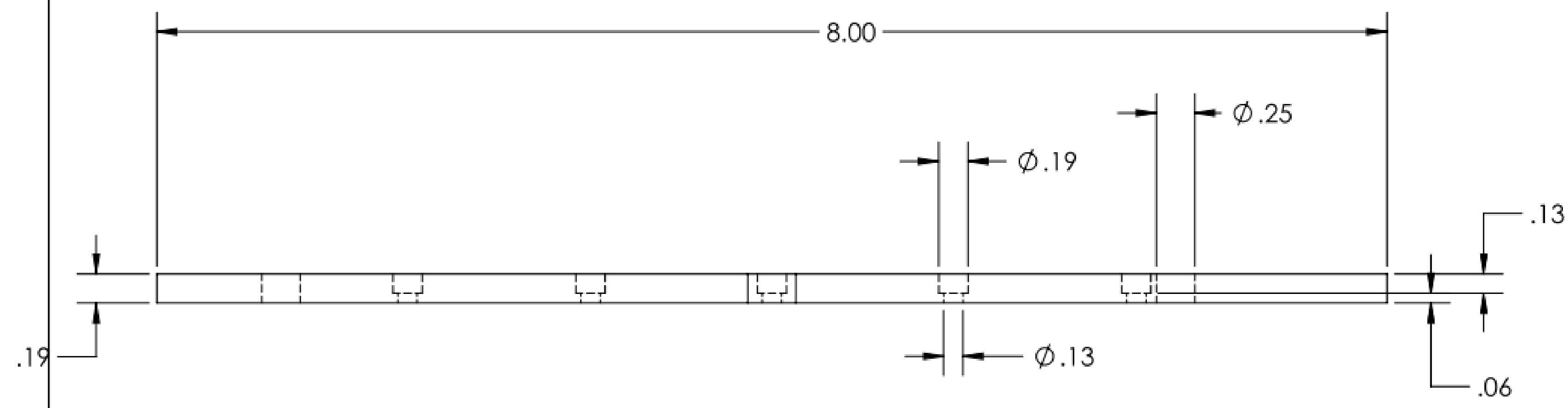
Drawing Set


8.00
5.00
8.00
5.00
.77
.19
.38
Ø.11
Ø.11
Ø.11
Ø.11
Ø.11
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF UNIVERSITY OF IDAHO, ME DEPARTMENT. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF UNIVERSITY OF IDAHO, ME DEPARTMENT IS PROHIBITED. BOOYA!
DEFAULT TOLERANCES:
LINEAR:
X.± .25
X.X± .1
X.XX± .01
X.XXX± .002
ANGULAR:
X.± 2
X.X± 1
X.XX± 0 30'
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL:
DESCRIPTION: Assembly (heatsink base, TEG, Plate)
CHECKED BY:
DATE:
DRAWN BY: Scott McMurdie
DATE: 5/4/2017
FILE NAME: Final Design Assembly (heat sink, TEGS, and plate).SLDPRT
Fire and Ice
UNIVERSITY OF IDAHO
MECHANICAL ENGINEERING
RC BAJA
PART #:
QTY:
SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF UNIVERSITY OF IDAHO, ME DEPARTMENT. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF UNIVERSITY OF IDAHO, ME DEPARTMENT IS PROHIBITED. BOOYA!	DIMENSIONS ARE IN INCHES THIRD ANGLE PROJECTION MATERIAL: Steel	Fire and Ice
DEFAULT TOLERANCES: LINEAR: X.±.25 X.X±.1 X.XX±.01 X.XXX±.002 ANGULAR: X.± 2 X.X± 1 X.XX± 0 30'	DESCRIPTION: Plate Design CHECKED BY: DATE: DRAWN BY: Scott McMurdie DATE: 5/4/2017 FILE NAME: Plate (Center Bolt 3-20) 2 bolts.SLDPRT	**UNIVERSITY OF IDAHO MECHANICAL ENGINEERING RC BAJA** PART #: QTY: SCALE: 1:2 SHEET: 1 OF 2



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DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

MATERIAL: Steel

Fire and Ice

UNIVERSITY OF IDAHO
MECHANICAL ENGINEERING
RC BAJA

DEFAULT TOLERANCES:

LINEAR:	ANGULAR:
X.±.25	X.± 2
X.X±.1	X.X± 1
X.XX±.01	X.XX± 0 30'
X.XXX±.002	

DESCRIPTION: Plate Design
CHECKED BY: DATE:
DRAWN BY: Scott McMurdie DATE: 5/4/2017
FILE NAME: Plate (Center Bolt 3-20) 2 bolts.SLDPRT
PART #: QTY:
SCALE: 1:2 SHEET: 2 OF 2

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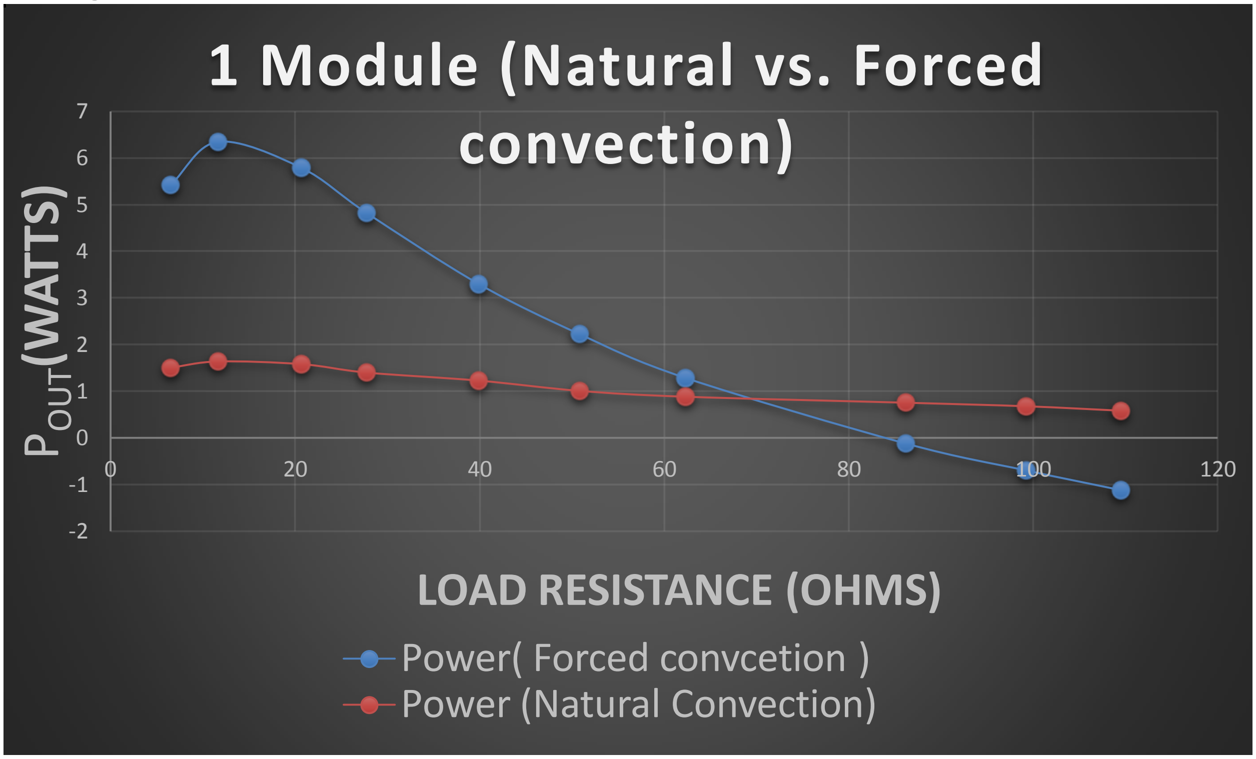
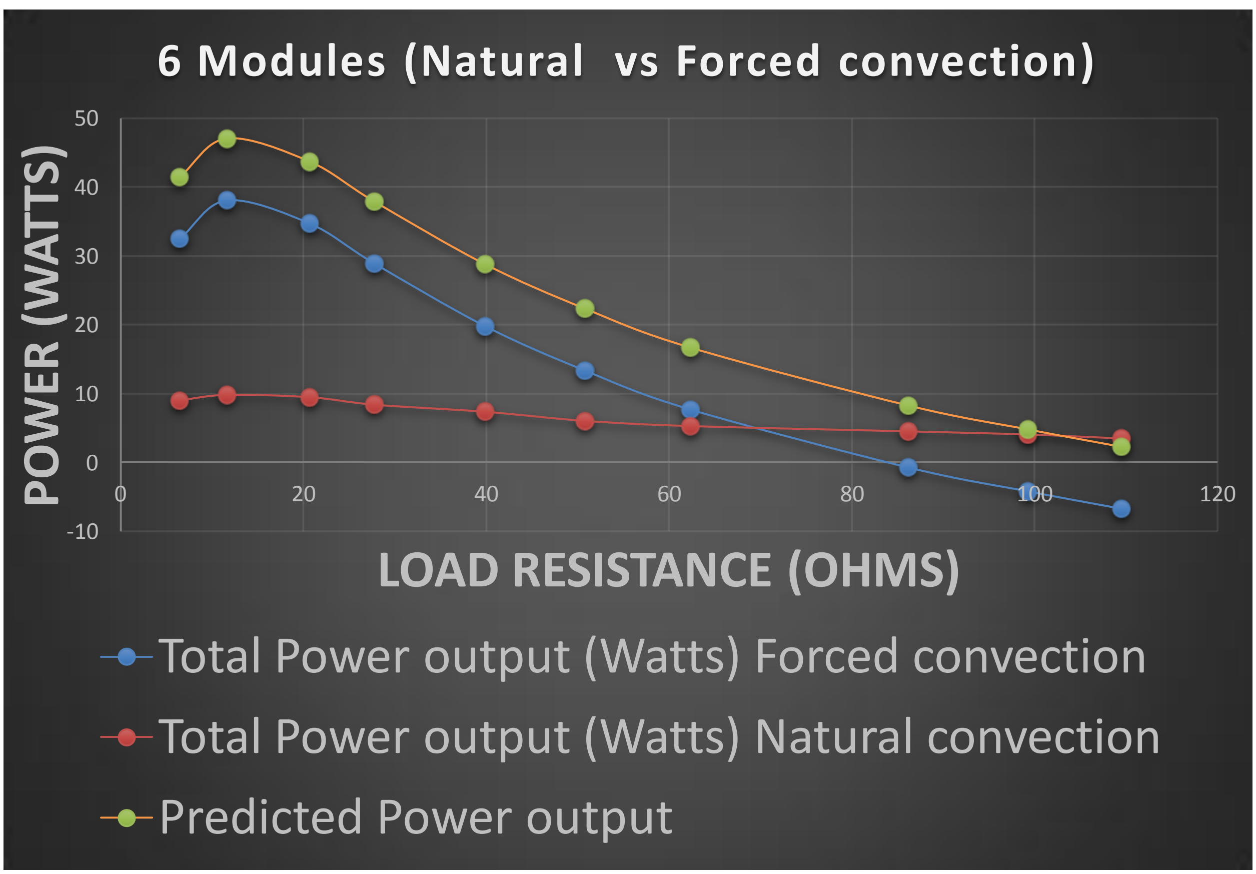
Testing Data





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Vendor data sheets:

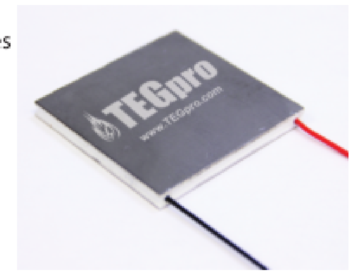
Thermoelectric Generators 22 Watt

TEGpro
Recycling waste heat for a cooler tomorrow

TE-MOD-22W7V-56
22 Watt Thermoelectric Module

Product Overview

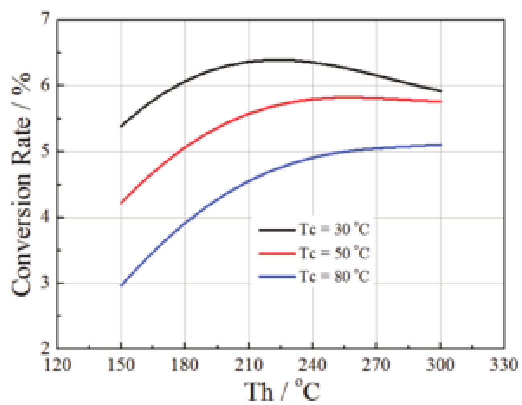
Our TEG power module is specifically designed and manufactured to convert high temperature heat sources directly into electricity. The Bi-Te based thermoelectric modules can operate at temperatures as high as 330 °C (626 K) continuously and up to 400 °C (752 K) intermittently. The module will generate DC voltage if there is a temperature difference across the module. Power is generated as the temperature difference across the module increases. The efficiency of the module will also increase as well. Thermally conductivity graphite sheets have been applied to both sides of the ceramic plates to provide low contact thermal resistance. Therefore you do not need to apply thermal grease or other heat transfer compound when you install the module. The graphite sheet works very well in high temperatures.



Specifications

Hot Side Temperature (°C)	300
Cold Side Temperature (°C)	30
Open Circuit Voltage (V)	14.4
Matched Load Resistance (ohms)	2.4
Matched load output voltage (V)	7.2
Matched load output current (A)	3.0
Matched load output power (W)	21.6
Heat flow across the module(W)	≈ 415
Heat flow density(W cm-2)	≈ 13.2
AC Resistance (ohms) Measured under 27 °C at 1000 Hz	1.1 ~ 1.35

Specification of the Module



Note: Conversion rate = Matched load output power/Heat flow through the module

Specifications subject to change without notice. Sep, 2014 - Rev 1.0

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TEGpro
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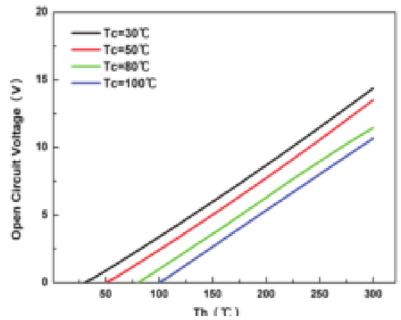
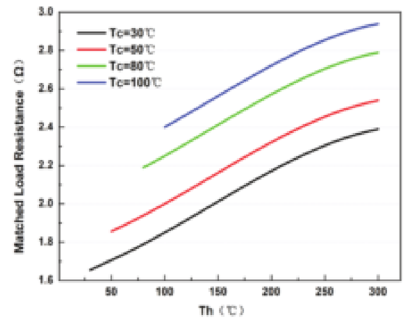
TE-MOD-22W7V-56
22 Watt Thermoelectric Module

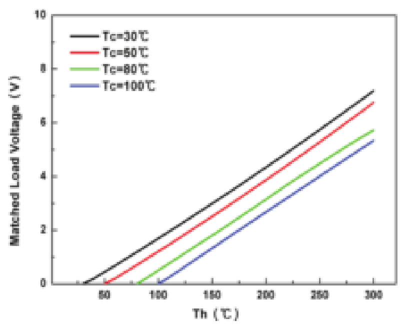
Performance



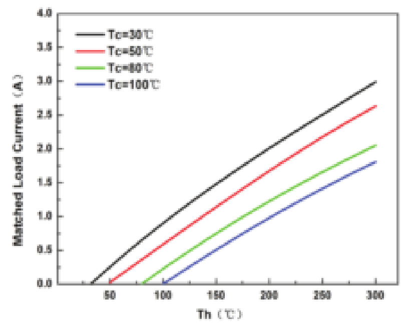
The chart for open circuit voltage Vs T_h under various T_c



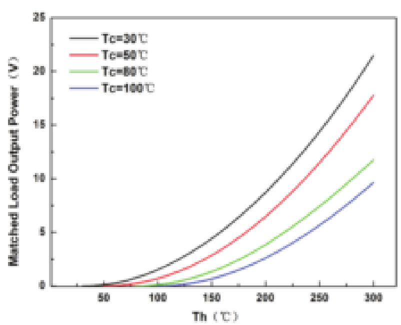
The chart for matched load resistance Vs T_h under various T_c



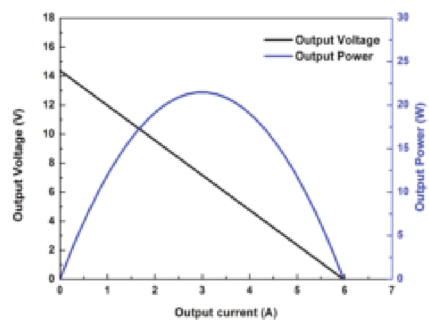
The chart for matched load voltage Vs T_h under various T_c



The chart for matched load current Vs T_h under various T_c



The chart for matched load output power Vs T_h under various T_c



The chart for output voltage and output power Vs output current under T_h=300 ℃ and T_c=30 ℃

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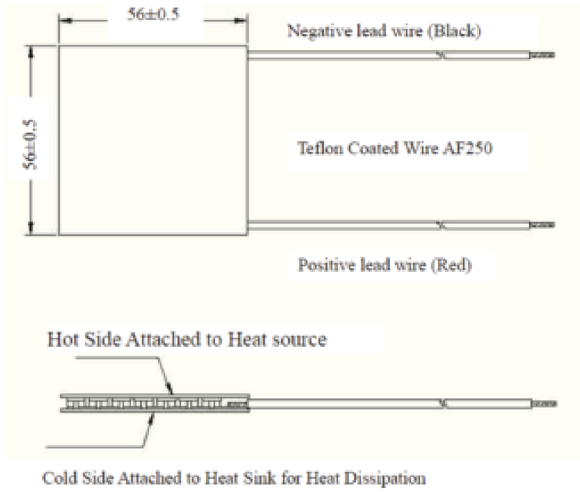
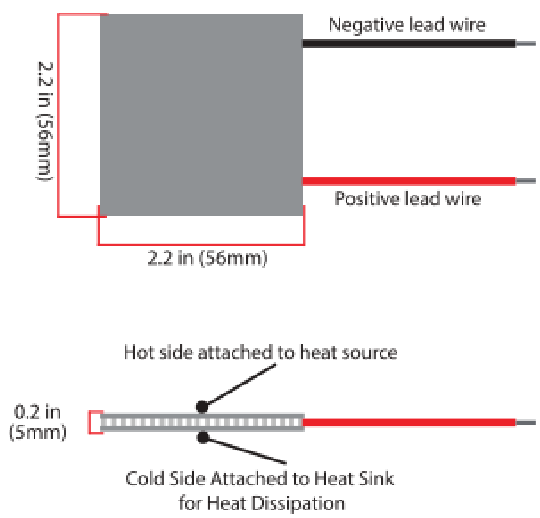
TE-MOD-22W7V-56
22 Watt Thermoelectric Module

Dimensions





Specifications subject to change without notice. Nov, 2014 - Rev 1.0

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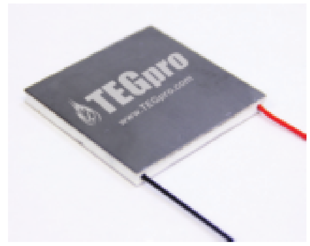
TEGpro™
Recycling waste heat for a cooler tomorrow

TE-MOD-18W9V-56
18 Watt Thermoelectric Module

Product Overview

Our TEG power module is specifcally designed and manufactured to convert high temperature heat sources directly into electricity. The Bi-Te based TEG power modules can operate at temperatures as high as 230 °C continuously. The module will generate DC voltage if there is atemperature difference across the module. Power is generated as the temperature difference across the module increases. The efficiency of the module will also increase as well. Thermally conductive graphite sheets have been applied to both sides of the ceramic plates to provide low contact thermal resistance. Therefore you do not need to apply thermal grease or other heat transfercompound when you install the module. The graphite sheet works very well in high temperatures.

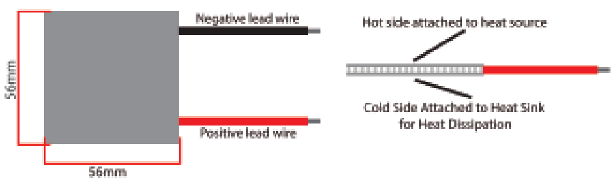


The Tegpro 18 Watt High Temperature Thermoelectric Module

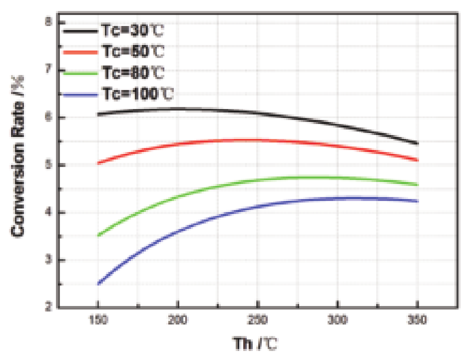
Specifications

Hot Side Temperature	320 °C
Cold Side Temperature	30 °C
Open Circuit Voltage (V)	17.7
Matched Load Resistance (ohms)	4.4
Matched load output voltage (V)	8.8
Matched load output current (A)	2.0
Matched load output power (W)	17.6
Heat flow across the module (W)	301
Heat flow density(W cm^{-2})	≈ 9.6
AC Resistance (ohms) Measur under 27 °C at 1000Hz	2.3 - 2.5

Geometric Characteristics



Conversion Rate of the modules Vs Th under various Tc



Noted: Conversion rate = Matched load output power/Heat flow through the module

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802.728.4533 P
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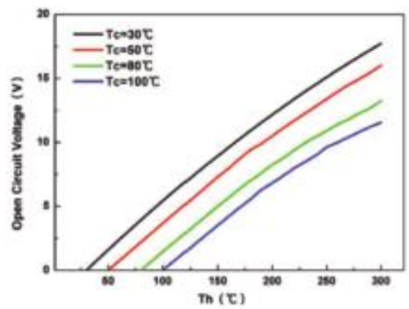
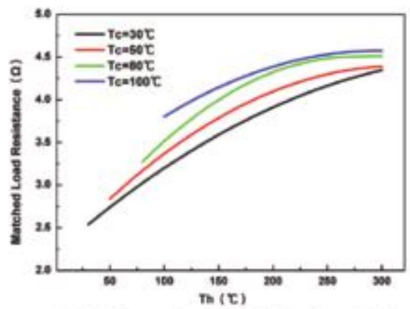
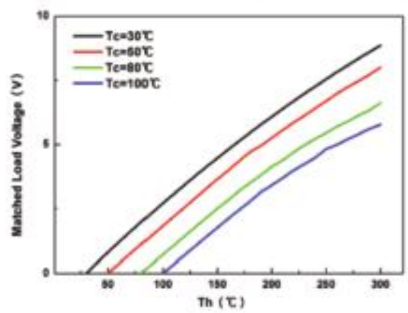
TE-MOD-18W9V-56
18 Watt Thermoelectric Module

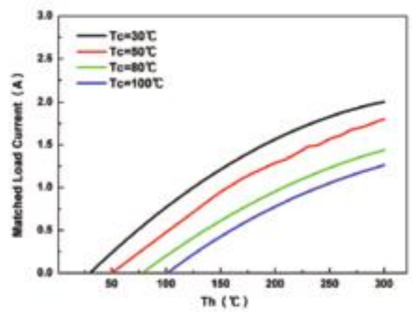
Module Performance





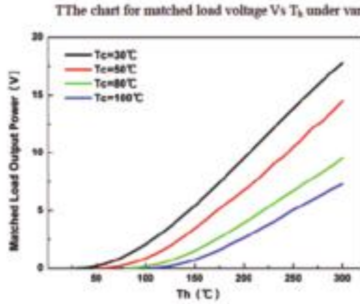
The chart for open circuit voltage Vs T_h under various T_c
The chart for matched load resistance Vs T_h under various T_c



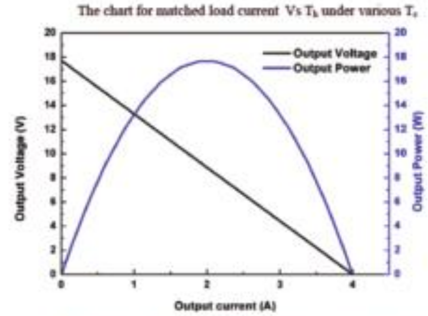


TThe chart for matched load voltage Vs T_h under various T_c

The chart for matched load current Vs T_h under various T_c



The chart for matched load output power Vs Th under various Tc



The chart for output voltage and output power Vs output current under Th=300□ and Tc=30□

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Heat Sink (3-505025G)

COOLINNOVATIONS ADVANCED HEAT SINKS

FOOTPRINT 5.00" X 5.00"

FLARED CONFIGURATION | ALUMINUM

SPECIFICATIONS

Overview

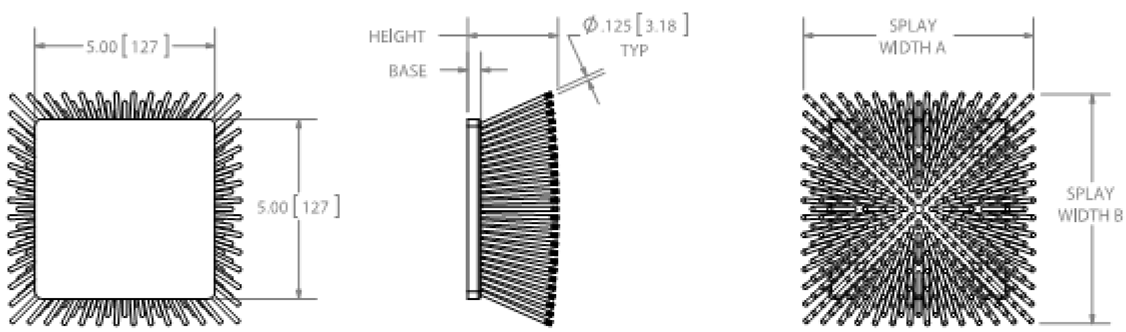
- Provides outstanding cooling power and low pressure drop
- Omnidirectional
- Recommended airspeed range: 0 to 600 LFM (0 to 3 m/s)
- RoHS compliant

Technical

- Material: Pure Aluminum
- Mfg. process: Cold forging
- Plating options: Black/clear anodize, chemical conversion coating
- Base finish: Lapped
  Flatness: Better than 0.001 in/in
  Surface roughness: 16 RMS

Flexible Parameters

- Footprint (length and width)
- Height (pin length & base thickness)
- Single or multiple pins can be eliminated
- Comprehensive machining (holes, threads, clearances, etc.)



A FLEXIBLE APPROACH: Parts can easily be modified to fit any application

P/N	Height in(mm)	Base in(mm)	Top (A) in(mm)	Top (B) in(mm)	Weight lb(g)	Thermal Resistance in °C/W 0(0)*	200(1)	400(2)	600(3)
3-505010G	1.00(25.4)	0.38(9.5)	5.29(134)	5.29(134)	1.13(511)	1.67	0.44	0.24	0.172
3-505012G	1.20(30.5)	0.38(9.5)	5.45(138)	5.45(138)	1.21(551)	1.37	0.34	0.191	0.147
3-505014G	1.40(35.6)	0.38(9.5)	5.61(143)	5.61(143)	1.30(590)	1.21	0.27	0.164	0.128
3-505016G	1.60(40.6)	0.38(9.5)	5.78(147)	5.78(147)	1.39(630)	1.07	0.23	0.143	0.113
3-505018G	1.80(45.7)	0.38(9.5)	5.94(151)	5.94(151)	1.48(669)	0.94	0.193	0.126	0.100
3-505020G	2.00(50.8)	0.38(9.5)	6.10(155)	6.10(155)	1.56(709)	0.82	0.167	0.112	0.090
3-505022G	2.20(55.9)	0.38(9.5)	6.26(159)	6.26(159)	1.65(748)	0.71	0.145	0.100	0.081
3-505024G	2.40(61.0)	0.38(9.5)	6.43(163)	6.43(163)	1.74(788)	0.61	0.128	0.090	0.073
3-505025G	2.50(63.5)	0.38(9.5)	6.51(165)	6.51(165)	1.78(808)	0.57	0.120	0.085	0.070

Disclaimer: www.coolinnovations.com

*Air Speed in LFM (m/s)

www.coolinnovations.com • sales@coolinnovations.com • Tel: (905) 760-1992 • Fax: (905) 760-1994

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Radio Charger

EV-Peak R1 200W 20Amp Touch Screen NiMH / LiPO Battery Balance Charger

Details

The R1 is compact and travel sized, intelligent battery charger with lots of great features. The charger can charge up to 200W (20A)*(Power supply not included)*. The back-lit LCD touch screen makes the simple menu a breeze to navigate all charging / discharging options. This charger includes a multi-charge cable with many different connectors allowing you to charge just about any battery. Charge LiIon, LiPo, LiPo High Voltage, LiFe 1-6 cells or NiCd, NiMH 1-15 cells with this compact charger.

Features

- Compact portable
- Graphical touch screen easy control
- Exclusive LiHV battery charging program
- Regenerative discharge
- Battery meter:cell voltage internal resistance
- 10 Battery memories
- Firmware upgradable
- End voltage adjustable(for expert user only)

Specifications

- DC Input Voltage: 11.0V-24.0V
- Charge Power: max.200W
- Discharger Power: max.30W
- Charge Current Range: 0.1~20.0A
- Discharge Current Range: 0.1~20.0A
- Regenerative Discharge Power: max. 200W
- Balance Current: 400mA
- LiPo/Li-Ion/LiFe/LiHV Battery Cell Count: 1-6 Series
- NiCd/NiMH Battery Cell Count: 1-15 Cells
- Pb Battery Voltage: 2V-24V
- Weight: 450g
- Dimensions: 102*120*46mm

`

Panaflo Case Cooling Fan

Panaflo Case Cooling Fan, 12Vdc, High

These fans (from Panasonic) suit a multitude of applications. Thanks to their unique "Hydro Wave" bearing system, these fans can create a respectable airflow at very low noise level. They're a great choice when it comes to cooling.
Size/Dimension: 120x120x38mm
Bearing: Type Hydro-wave (HWB)
Connector Type: 12" Lead wires
Voltage: Rated 12V DC
Power: Rated 4.44 W
Speed: 2500 RPM (Medium speed with RPM sensor)
Air Flow: 103.8 CFM
Noise: 41.5 dBA
RoHS Compliant
CSA and UL Component Listed
Panasonic-NMB-MAT
FBA-12G12H1BX

`

Bill of Materials

Bill of Materials								
Deliverables	**Component**	**Part number**	**Part Description**	**Vendor**	**Qty**	**Units**	**Price**	**Cost**
6 Modules	Thermoelctric Generator(TEG)	TGPR-22W-7V-56S	Tegpro High Temperature TEG Power Module - 22Watt 7 volt 56 mm	Tegmart.com	24		$57.50	$1,380.00
	Heat Sinks	3-505024G	5x5x2.5 flared pin fin	coolinnovations.com	6		$40.00	$240.00
	Steel for bracket		6x6x3/16 plates	Facilities	6			$0.00
	Graphit Sheets	P14965-ND	PGS SHEET 115X180MM W/POLYESTER	digikey.com	10		$10.68	$106.80
Module	Nuts	91841A005	18-8 Stainless hex nut	mcmaster.com	1	100	$2.61	$2.61
	Lock washer	95584A200	18 -8 Stainless Steel #4	mcmaster.com	1	100	$2.03	$2.03
	Screws	91251A115	4-40 1" Steel cap screws	mcmaster.com	2	100	$5.40	$10.80
Fan	Fan	RP7075	Panaflo Case Cooling Fan, 12Vdc, High	/www.skycraftsurplus.com	6		$9.95	$59.70
Radio Charger	Battery Charger		EV-Peak R1 200W 20Amp Touch Screen NiMH / LiPO Battery Balance Charger	getfpv.com	1		$69.99	$69.99
	Barrel Jack	CP3-1000-ND	CONN PWR PLUG 2.1X5.5MM SOLDER	digikey.com	10		$0.91	$9.10
Transmission of Electricity	8 AWG 3 conductor cable			mcmaster.com	60	feet	$2.51	$150.60
	12 circuit terminal block	7527K33	16-6 AWG wire, 12 circuit terminal block	mcmaster.com	1		$24.50	$24.50
	20 circuit terminal block	7527K41	22- 12 AWG wire, 20 cicurit terminal block	mcmaster.com	1		$7.67	$7.67
	Voltage Regulator	HVI-FN-12	TEG Power Thermoelectric Generator Fan Drive Module	Tegmart.com	1		$13.99	$13.99
							Total	**$2,077.79**

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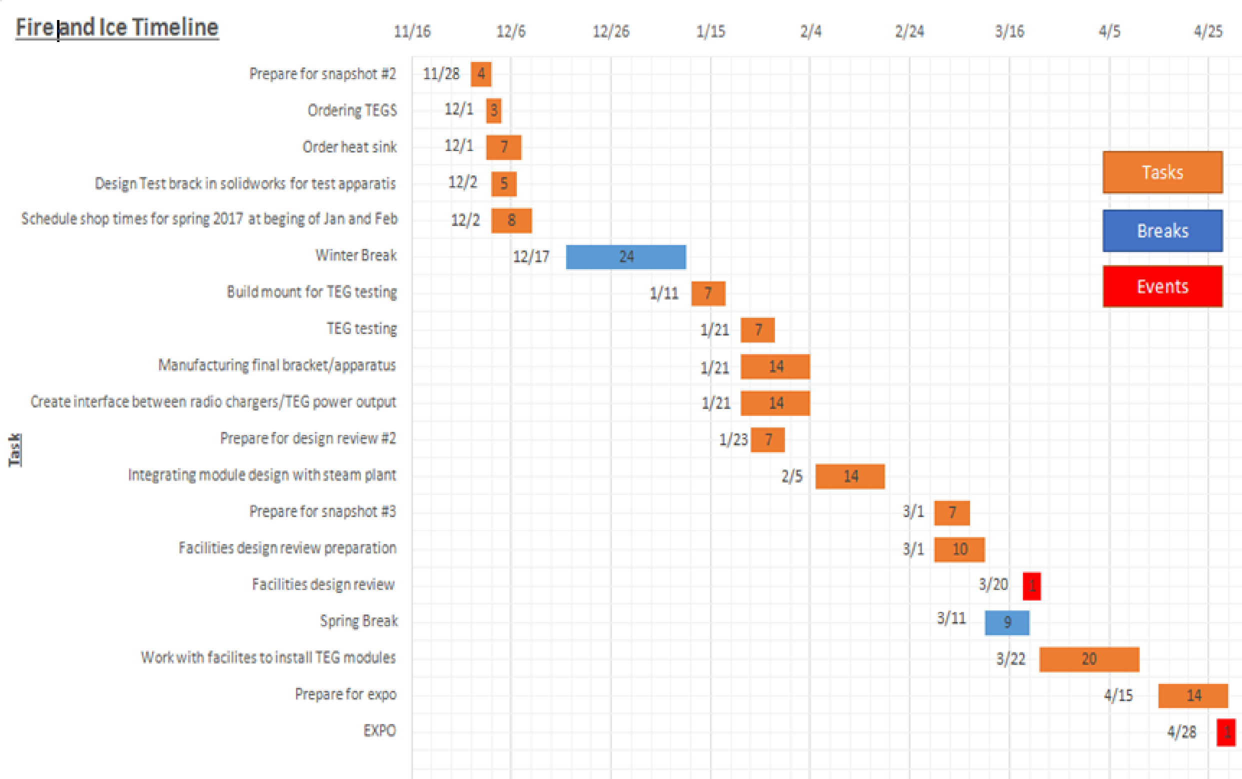
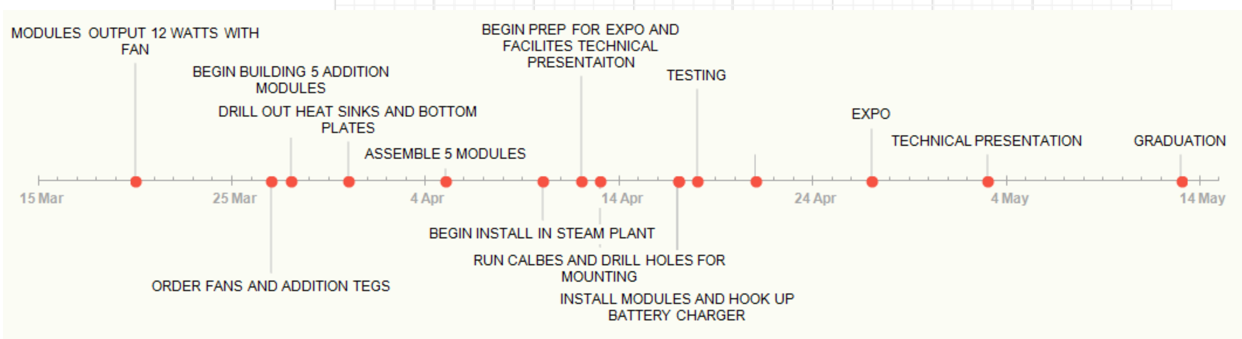
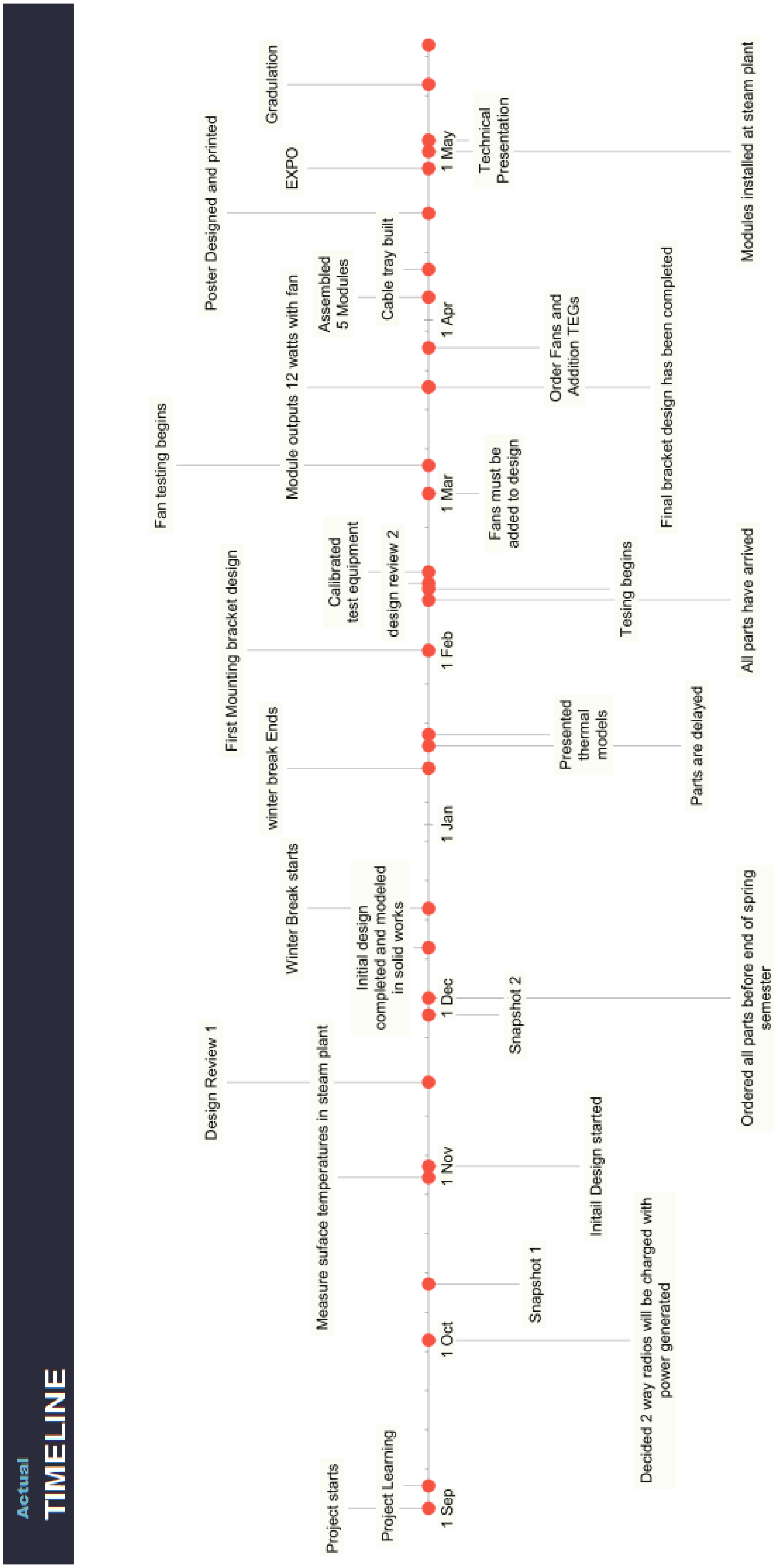
Project Schedules

Originally planned at start of project





Executed at end of project



DFMEA worksheet

Item:	Waste Heat Recovery System	Responsibility:	Facilities
Model:		Prepared by:	B.Perkins
Core Team:	B.Nafsinger, S. McMurdie, G. Oman, B. Perkins		
FMEA number:	1.3		
Page :	1 of 1		
FMEA Date (Orig):	4/27/2017	Rev:	2

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
Energy Recovery	TEG Failure	Decrease in power, Increased charging times	2		Frequent shutdowns and restarts	2	None	3	12	Replace Faulty TEG	Maintance should replace the TEG at the next boiler shutdown	Replace TEG	2	2	3	12
	Fan Failure	Decrease in power, Increased charging times	2		Reach Lifespan of fan	4	Replace Fans at Scheduled intervals	3	24	Replace Faulty Fan	Fan should be replaced as soon as possible	Replace Fan and Clean regularly	2	2	3	12
	Module Damage	Total system failure	4		Errant tool or equipment damages the system	1	Modules are out of the way and not in danger of damage	1	4	Repair damage	Repair as soon as possible	Replace Damaged parts or wiring	4	1	1	4
	Wire damage due to heat	Decrease in power, Increased charging times, Total system Failure	4		Ambient Tempature exceeds wire rating, Short circuit	1	Ensure adiquate ventalation near boiler	2	8	Replace damaged wires	Repair as soon as possible	Replace Wires	4	1	2	8
	Electrical circuit damage	Outside force causing a short	5		Circuit shorted to ground	1	None	1	5	Replace Damaged componets, Install protection breaker	Repair As soon as possible	Install Breaker	2	1	1	2

Rating	Score	Guide
Severity	1 to 5	1- Insignificant consequence of failure
		5- Catastrophic consequence of failure possibility for injury
Occurance	1 to 5	1- Low probability of failure occuring
		5- High probability of failure occuring
Detection	1 to 5	1- High probability failure will be detected
		5- Low probability failure will be detected

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Electronic Archive Arrangement