Performance Review Agenda:

1. One page summary- Project description
2. Roles and responsibilities
3. Engineering specifications
4. Final bill of materials
5. Design concept
6. Concept breakdown
7. Design verification
8. Testing results
9. Thermal model comparison
10. Electrical issues
11. Future improvements and lessons learned

Project #	**Project Name**	**Project Track**	**Project Family**
P08441	Auto Exhaust Power Generation Unit from Waste Heat	Sustainable Products, Systems, and Technologies	Next Generation Thermo-Electric Systems
Start Term	**Team Guide**	**Project Sponsor**	**Doc. Revision**
2007-2	2007-3	RIT ME Department	3

Project Description

Project Background:

The motivation for this project stems from an increasing need for highly efficient power generation in the transportation sector. Thermoelectric power generation is seen as a possible step in gaining efficiency in an economical manner. Furthermore, motivation lies in the general understanding of the operation and feasibility of thermoelectric power recovery. P08441 will build upon two previous Senior Design projects by implementing integral testing equipment which has already been designed.

Furthermore, the RIT Mechanical engineering department has the desire to build its competency and knowledge base with thermoelectric power generation. This project will ideally lead to a better understanding of thermoelectrics and their viability as a form of renewable energy.

Problem Statement:

This project's mission is to design an efficient thermoelectric module to attach to a test fixture realistically modeling a chosen vehicle's dynamics. Additionally the power generated is meant to make the vehicle more fuel efficient by running a subsystem.

Objectives/Scope:

1. Realistically simulate an actual vehicle using the test stand.
2. Design an efficient thermoelectric module to maximize heat recovery and electrical output.
3. Power an important vehicle subsystem using electricity generated by the thermoelectric module. For example, run headlights or charge vehicle battery.

Deliverables:

- Fully operational exhaust heat recovery unit.
- Heat recovery unit should be fully tested and characterized for a range of driving conditions.
- Heat recovery unit will power vehicle subsystem or charge the battery.
- Conference paper and technical poster describing project

Expected Project Benefits:

- There will be a better understanding of thermoelectric operation and the feasibility of applying thermoelectric technology to an actual vehicle.
- There will be an increase in operating of efficiency of the chosen vehicle because the thermoelectric generator will run an important vehicle subsystem or charge the battery.
- There will be a thermoelectric heat recovery unit that can be used in future students' labs and used for validation of models.

Core Team Members:

- Stephen Byrne
- Mike Rheinheimer
- Erin Crowley
- Paul Gaylo
- Joel Nelson
- Frank Trotto

Strategy & Approach

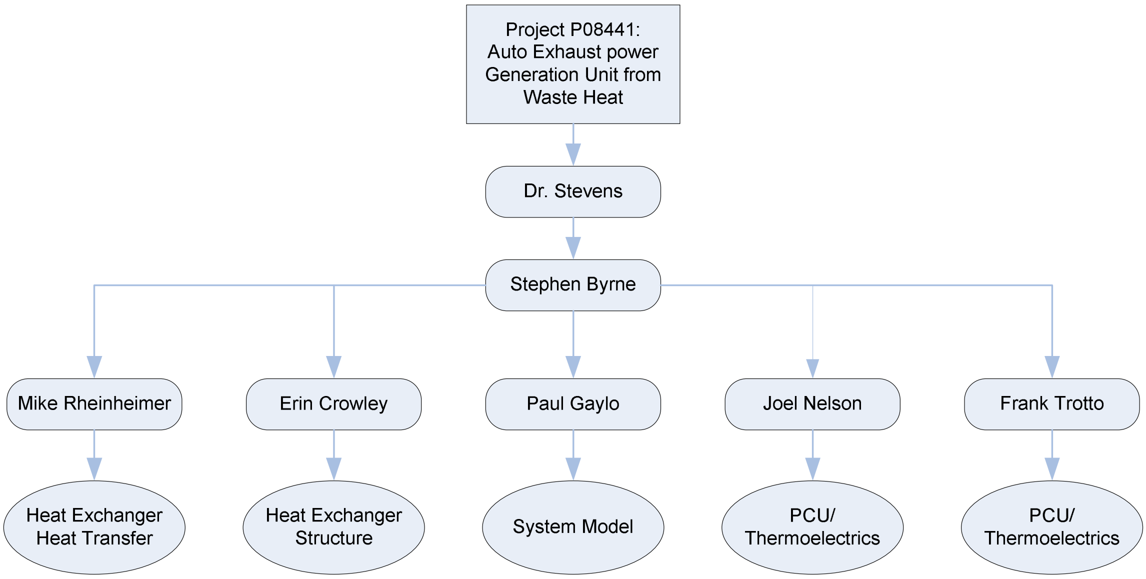
Assumptions & Constraints:

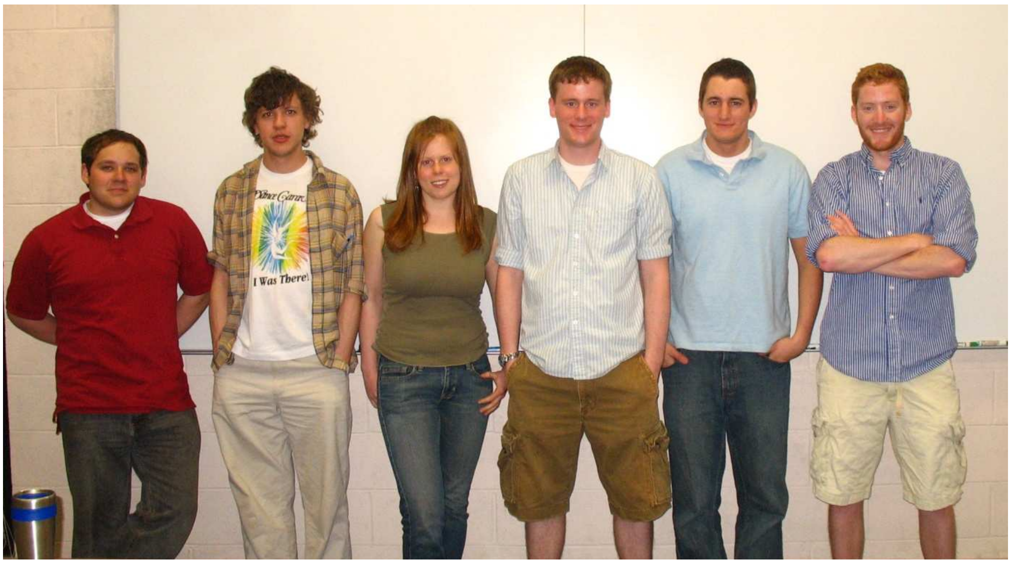
1. Current thermoelectric generator technology is not very efficient, typically less than 5% efficient, and has specific temperature limitations that must be adhered to.
2. The limitations of the test stand will limit the complexity and realism of our model.
3. Creating an effective temperature drop across the thermoelectric will be very challenging. It will be difficult to adequately cool the cold side of the TEG to maximize performance.
4. The budget for the project will be $3,000.

Issues & Risks:

- No team member has had extensive experience with finite element software for heat transfer aspects or CFD for fluid flow aspects of the project.
- Collecting critical data from an actual exhaust system may be difficult without becoming invasive.
- Current thermoelectric technology is not very efficient and has specific temperature properties which must be adhered to.
- Thermoelectric lead time is about 4-6 weeks

Name	Project Area of Responsibility	Functional Area of Responsibility	Hardware Area of Responsibility	Role	e-mail	Phone Number
Roberts Stevens	Guide	Mechanical Support	General	Customer	rjseme@rit.edu	585-475-2153
Stephen Byrne	Team Lead	Flow Modeling	Heat Exchanger Structure	ME Support	srb7109@rit.edu	802-779-4883
Mike Rheinheimer	ME 1	Thermal modeling	Heat Exchanger Heat Transfer	ME Support	mer5067@rit.edu	585-224-5184
Erin Crowley	ME 2	Structural modeling	Heat Exchanger Structure	ME Support	ecc2553@rit.edu	202-207-6937
Paul Gaylo	ME 2	System/vehicle modeling	System Model	ME Support	pjg6713@rit.edu	607-346-5528
Joel Nelson	EE 1	Electrical support	PCU/Thermoelectrics	EE Support	jrn2673@rit.edu	802-558-1487
Frank Trotto	EE 2	Electrical support	PCU/Thermoelectrics	EE Support	fmt0375@rit.edu	585-613-1568





P08441 Auto Exhaust Power Generation Unit from Waste Heat

Metric #	Need	Metric	Importance	Units	Marginal Value	Ideal Value
1	1.1	Appropriate exhaust temp.	7	Kelvin	500	550
2	1.1	Appropriate exhaust flow	7	kg/s	0.02	0.04
3	1.1	Appropriate exhaust material: melting point	8	Celsius	1000	1500
4	1.2	Temperature range for test fixture	7	Celsius	300-400	300-600
5	1.2	Flow range for test fixture	7	kg/s	.02-.06	.01-.08
6	2.1	High thermoelectric module efficiency	7	%	1.5	2
7	2.2	Suitable thermoelectric max operating temperature	6	Celsius	200	225
8	2.2	TE can withstand vibrations and shocks	3	1 Foot Drops	3	5
9	2.3	Adequate power generation	9	W	65	100+
10	2.4	Thermoelectric is optimized for temperatures that we are able to model	7	Celsius	130	230
11	2.5	Low cost for thermoelectrics	6	$/TE	<200	<100
12	3.1	Average upstream hot side of TEG @ proper temp.	7	Celsius	200	225
13	3.1	Average downstream hot side temperature are adequate	7	Celsius	130	160
14	3.2	Average cold side temperature at proper temperature	7	Celsius	100	40
15	3.3	Appropriate exhaust material: pipe surface does not oxidize or corrode	3	Flow reduction (Pa)	50	0
16	3.4a	Negligible Pressure Drop	5	Pa	1100	500
17	3.5	Low cost for a mass production unit	4	$	1500	500
18	3.6	Maintain adequate contact pressure (set by supplier)	5	psi	225±75	225±25
19	3.8	Reasonable size, specifically height	4	m	0.25	0.15
20	4.1	Run Vehicle Sub System	8	n/a	battery	head lights
21	4.2	Verify efficiency increase of vehicle	8	%	0.5	1
22	4.3	System output voltage	6	Volts	14±3	14±1
23	5.1	Durability of System	3	Years	5	10
24	6.1	User protected from electrical and thermal components	9	Accidents	<1	0
25	7.1	System parameters easily obtained from testing	6	Labview Compatible	Mostly	Yes

Bill of Materials:

Electric Purchased Components

Part #	Description	Unit Cost ($)	Quantity	Total Price ($)	Product Sales/ Manufacturer	Lead Time
HT8-12-40	TEG	25.3	48	1214.4	Melcor	4 wks
438-1043-ND	PCB Board	26.39	1	26.39	Digi-Key	
LT3724EFE#PBF	Voltage Regulator	3.69	2	7.38	Linear Technology	5-10 dys
IRF1010ZPBF-ND	Power Transistors	3.16	2	6.32	Digi-Key	4 wks
NA	Resistors	0		0	EE Lab	NA
TCH35PR100JE-ND	Resistor (.025 ohms)	8.78	4	35.12	Digi-Key	4wks
NA	Capacitor	0		0	EE Lab	NA
TR33-12	Battery	52.7	1	52.7	Batteryspec	1 day
M8929-ND	Inductor (47uH)	4.29	2	8.58	Digi-Key	4wks
8TQ060PBF-ND	Diode (Schottky)	1.6	3	4.8	Digi-Key	4wks
MBRS360CT-ND	Diode	1.48	1	1.48	Digi-Key	4wks
1N4148	Diode	0	1	0	EE Lab	1 dy
568-1668-5-ND	Diode	1.44	1	1.44	Digi-Key	4wks
F2519-ND	Fuse	0.266	5	1.33	Digi-Key	4wks
F1498-ND	Fuse Terminal	0.99	2	1.98	Digi-Key	4wks
	SMT PCB	46.99	1	46.99	Digi-Key	
HS300-ND	Heat Sink	1.46	6	8.76	Digi-Key	4wks
			Sub Total	**$1,417.67**		

TEG Structure Purchased Components

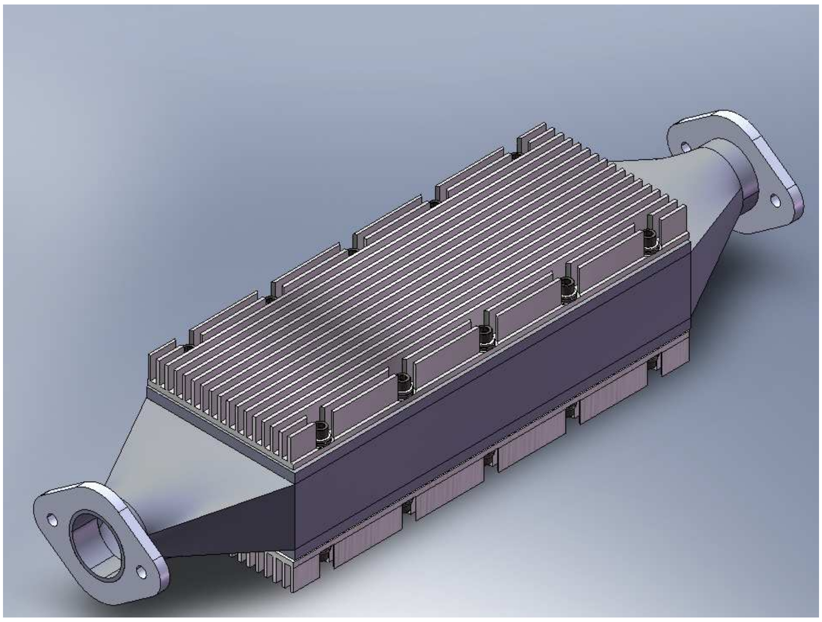
Part #	Description	Unit Cost ($)	Quantity	Total Price ($)	Product Sales/ Manufacturer	Lead Times
E1451UX8-00	Extruded Heat Sink	125	2	250	dkober@electrasales.com	3 wks
SMC Metal	Top & Bottom Plate (6061 AL)	47	1	47	SMC Metal	1 wk
SMC Metal	6061 Al Fin Material	108	1	108	SMC Metal	1 wk
SMC Metal	6061 Al Flange Material	13	1	13	SMC Metal	
SMC Metal	6061 Side wall	9	1	9	SMC Metal	3 wks
Custom	Transitions	75	2	150	Bellintecoolers.com	2 wk
91251A582	Black-Oxide Steel 5/16"-18 Socket Head Cap Screws (50 Pack)	8.82	1	8.82	http://www.mcmaster.com/	1 wk
9294K59	Bellvue Disc Springs	2.32	20	46.4	http://www.mcmaster.com/	1 wk
91090A110	5/16" washers (100 Pack)	3.74	1	3.74	http://www.mcmaster.com/	1 wk
8925A31	End Mills	14.45	2	28.9	http://www.mcmaster.com/	1 wk
907GF	Resbond 907 GF Thermal Adhesive	32.95	1	32.95	www.cotronics.com	1wk
81164	Permatex 26B	4.74	1	4.74	www.permatex.com	
597-A	Pyro-Duct Paste	175	1	175	www.aremco.com	1 wk
ot-201	Omega Thermal Grease	25	2	50	www.omega.com	1 wk
			Sub Total	**$677.55**		

Testing Needs

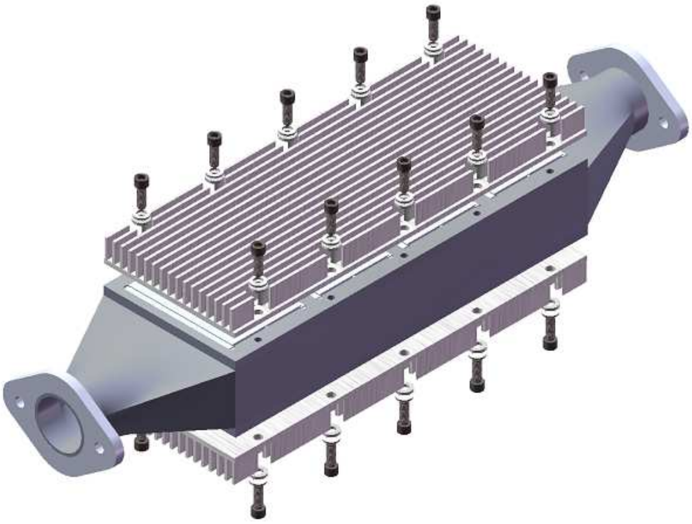
Part #	Description	Unit Cost ($)	Quantity	Total Price ($)	Product Sales/ Manufacturer	Lead Time
	Toro Power Sweep	25	2	50	Home Depot	1wk
KQXL-116U-12	Thermocouples	30	2	178	Omega	1wk
			Sub Total	**$228.00**		
			Grand Total	**$2,323.22**		

Design Concept:

The figure below illustrates the final concept. The design consists of finned heatsinks to allow air cooling, which could be applicable for automotive use, considering the prevalent air flow.



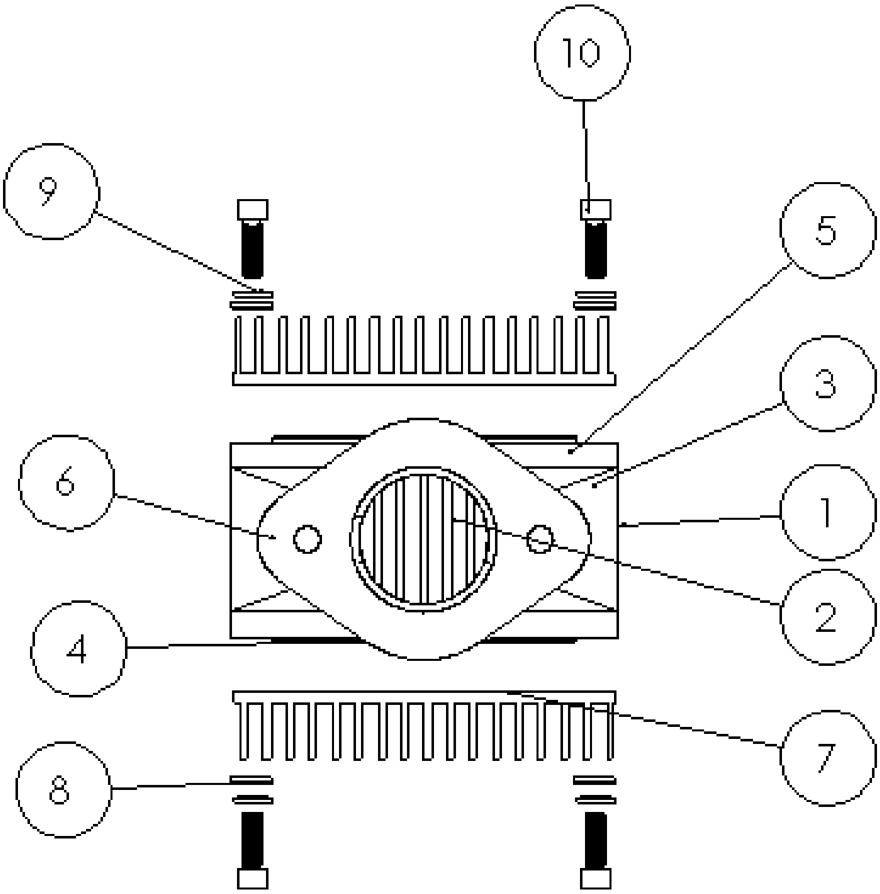
Below is a diagram of the assembly of the final concept which demonstrates the bolt and washer placement. It also shows the placement of the thermoelectrics. The duct is internally finned.



P08441 Auto Exhaust Power Generation Unit from Waste Heat

Component Breakdown:

Item No.	Part	Description	Quantity
1	SIDE WALL	3/8" ALUM.	2
2	Internal Fins	1/8" THICK ALUM.	15
3	DIFFUSER	PURCHASED PART	2
4	TE		48
5	Top & Bottom Plate	1/2" THICK ALUM.	2
6	FLANGE	PURCHASED PART	2
7	HEAT SINK	16" LONG PURCHASED PART	2
8	WASHER	5/16" DIA.	40
9	BELVUE SPRING		20
10	BOLT	5/16" DIA.	20



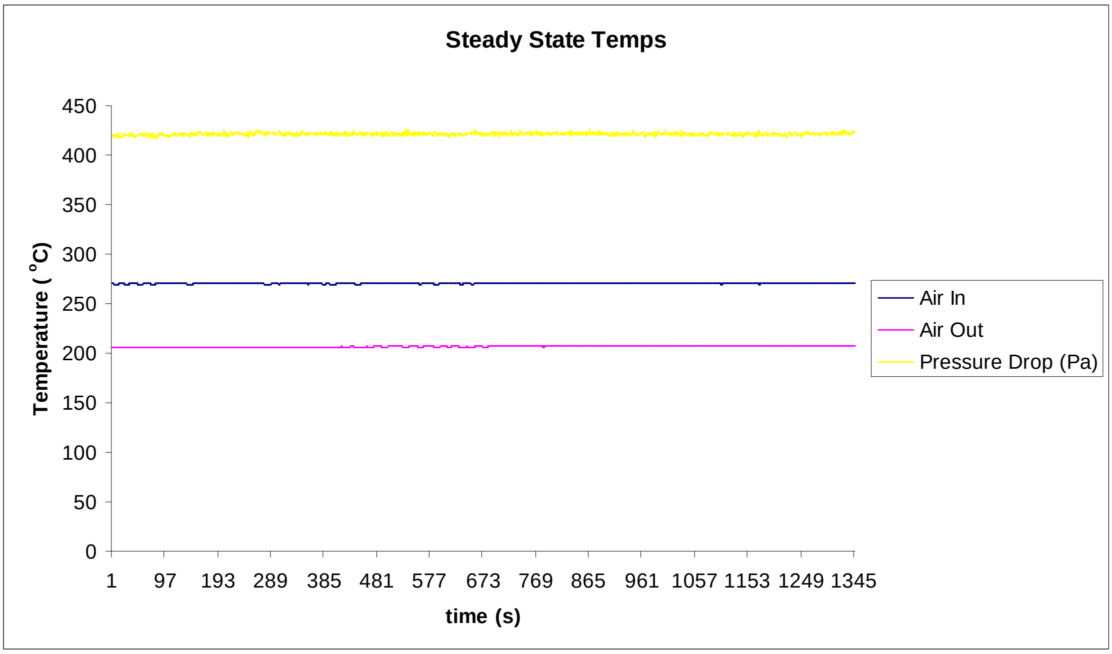
Metric	Need	Test Plan	Units	Marginal Value	Ideal Value	Tested Value
1	Appropriate exhaust temp.	T_{INLET} will ensure that the exhaust gas temperature entering is an appropriate temperature for operation.	Kelvin	500	550	453
2	Appropriate exhaust flow	The test stand has a flow meter built in. The flow can also be adjusted over a range from .01-.08kg/s on the test stand.	kg/s	0.02	0.04	0.04
3	Appropriate exhaust material: melting point	The melting point of the 6061 Aluminum being used is over 1000C while the temperatures that the aluminum will experience will be 400C as a maximum.	Celsius	1000	1500	YES
4	Temperature range for test fixture	The test fixture has the ability to range from 300-600C. Furthermore, the T_{INLET} thermocouple will measure the incoming exhaust gas temperature.	Celsius	300-400	300-600	YES
5	Flow range for test fixture	The specification is within the test stand limitations and will be monitored with the built in flow meter.	kg/s	.02-.06	.01-.08	YES
6	High thermoelectric module efficiency	The thermoelectric efficiency will be determined under the **Standard Test Conditions**. $\eta_{Thermoelectric} = \frac{P_{Output}}{kA(T_{Hot} - T_{Cold})t}$ The THot and TCold temperatures come from the thermocouple readings. The k is a given spec from manufacturer of the thermoelectrics and both the thickness and area are measurable.	%	1.5	2	NO
7	Suitable thermoelectric max operating temperature	The maximum operating tempertaure of the Melcor thermoelectrics is 225C.	Celsius	200	225	YES
8	Adequate power generation	To obtain the maximum power generation the thermoelectrics will be attached to a load, a rheostat or similar, and the power supplied to the load will be measured as the load is varied under the **Standard Test Conditions**.	W	65	100+	NOT CURRENTLY
9	Thermoelectric is optimized for flow temperatures that we are able to model	We need to ensure that we are maximizing the potential of our thermoelectric by creating the largest temperature difference possible. To measure this number we will take the reading from the thermocouples on the hot side and subtract the temperature from the thermocouples on the cold side (both from the inlet end).	Celsius	130	230	110
10	Low cost for thermoelectrics	The thermoelectrics that we are ordering are under $30 each. This easily meets the specification.	$/TE	<200	<100	YES
11	Average upstream hot side of TEG @ Proper Temp.	Thermocouples will be attached under the upper and lower foremost thermoelectrics on the hot side to monitor the hot side temperature. The maximum temperature the Melcor models can operate at is 225C. An average will be taken between the two thermocouples.	Celsius	200	225	NO

12	Average downstream hot side temperatures are adequate	Thermocouples will be attached under the upper and lower downstream thermoelectrics on the hot side to monitor the hot side temperature. The maximum temperature the Melcor models can operate at is 225C. An average will be taken between the two thermocouples.	Celsius	130	160	YES
13	Average cold side of TEG@ proper temp.	Thermocouples will be attached under the foremost and the furthest thermoelectrics on the cold side to monitor the cold side temperature. An average of the four readings will be taken.	Celsius	100	40	YES
14	Appropriate exhaust material: pipe surface does not oxidize or corrode	Pictures of the inner surface will be taken before any testing is done and after each test performed. Any changes noted upon visual inspection will indicate that corrosion has occurred on the surface of the metal.	Flow reduction (Pa)	50	0	YES
15	Negligible Pressure Drop	The pressure sensors on the thermoelectric test stand will be able to measure the pressure of the gas entering and exiting the TEG structure. The difference between P_{IN} and P_{OUT} will give the pressure drop.	Pa	1100	500	YES
16	Low cost for a mass production unit	We will price out each component as if we were buying it in mass quantity and subtract the testing materials from the BOM for a high production unit.	$	1500	500	NOT YET CALC. UNDER BUDGET
17	Maintain adequate contact pressure (set by supplier)	To measure the contact pressure on the thermoelectrics we can use the bolt torque. By measuring the bolt torque at steady state operation we can back out the resultant bolt load and thereby get the equivalent pressure on the thermoelectrics. Furthermore, we will first run a test with pieces of steel in the place of the thermoelectrics and then measure the bolt torque to find the resultant pressure.	psi	225±75	225±25	NOT FULLY TESTED
18	Reasonable size, specifically height	The height of the system can be simply measured using a ruler. The measurement will be from the tops of the fins of each of the heatsinks.	m	0.25	0.15	YES
19	Run Vehicle Sub System	The ability to charge a battery can be determined by measuring the voltage across the battery. A slightly discharged battery, with a lower voltage, will be attached to the system and, after charging, an increase in the battery voltage, from approximately 11 V to 12.65 V, shall be verified. Test will be performed under **Standard Test Conditions**.	n/a	battery	head lights	NOT YET TESTED
20	Verify system efficiency	The system efficiency will be tested under the Standard Test Conditions and verified with the following equation: $\eta_{System} = \frac{P_{Output}}{\dot{m} C_p (T_{Exit} - T_{Inlet})}$ The mass flow rate is measurable and will be known in the standard test conditions. The inlet and outlet temperatures of the gas can be measured from thermocouples in the test fixture.	%	0.5	1	NO
21	System output voltage	The output of the battery charging circuitry will be measured while attached to a load under the **Standard Test Conditions**. This should be sustained while varying the test conditions. After running for 1 hour under **Standard Test Conditions** with a variety of loads, the output of the regulator should again be verified.	Volts	14±3	14±1	NOT YET TESTED

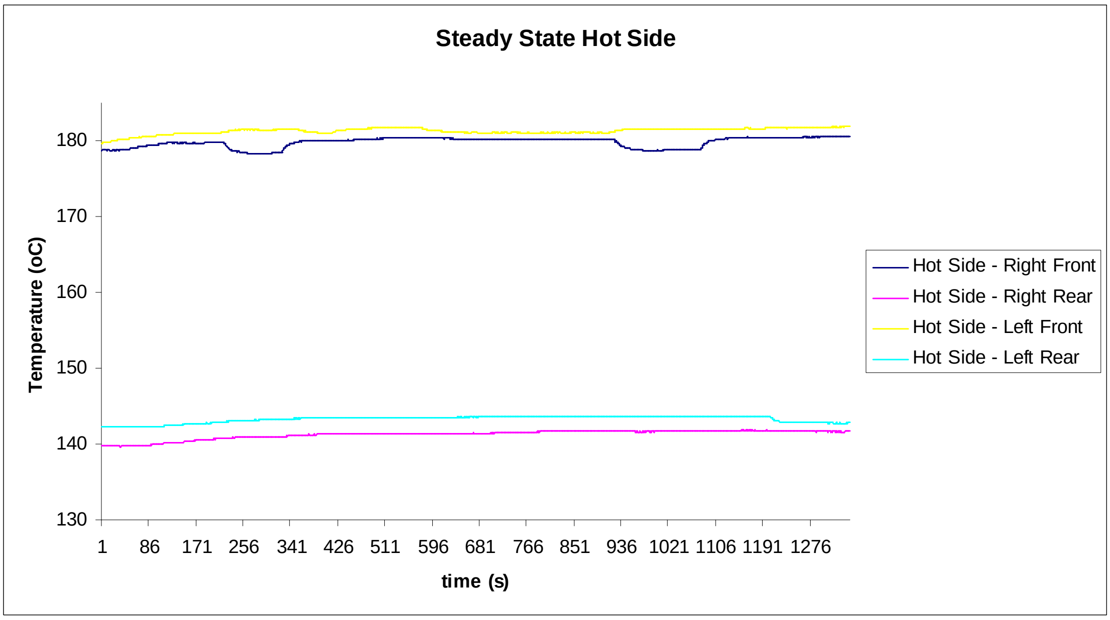
22	Durability of System	The design of the system is such that there are no moving or complex parts.	Years	5	10	YES
23	User protected from electrical and thermal components	The thermoelectrics will be inspected before use to ensure that all electrical components are insulated. Furthermore, the wiring scheme will be inspected before testing. Protection diodes and fuses will be implemented to prevent over-current states.	Accidents	<1	0	YES
24	System parameters easily obtained from testing	The placement of the thermocouples will allow easy attachement to the DAQ.	Labview Compatible	Mostly	Yes	YES

Testing Results:

The input exhaust characteristics are given in the chart below. The graph describes the steady state pressure drop, in Pascals, and exhaust air inlet and outlet temperatures.

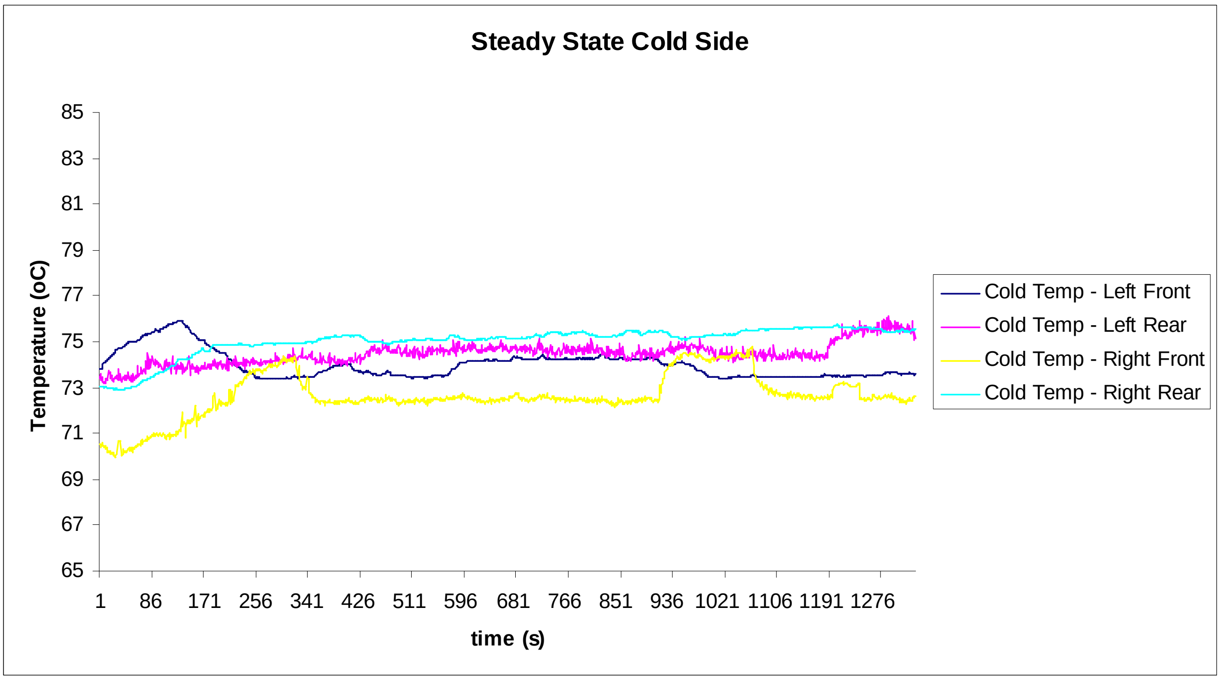


The steady state hot side temperatures, both upstream and down, were recorded using thermocouples attached to a data acquisition unit. The graph indicates a temperature drop from front to back of about 40 degrees Celcius.



Testing Results:

The cold side temperature readings are outlined in the graph below. The temperatures are all quite close to each other, which indicates that there is not a temperature drop from front to back as was expected.



The cold side temperatures are approximately 30 degrees Celsius higher than originally calculated. Possible reasons for this discrepancy:

- Actual heat sink thermal resistance is higher than manufacturer rating, reducing its ability to cool.
- The blower air may be having trouble flowing through the fins, which reduces the amount of heat loss through convection, thereby increasing the heat sink temperature.
- Thermal shorting from the bolts. The bolts may be drawing heat from the internal duct and transferring it directly to the heat sink. This possibility was explored in the thermal model and did not seem to pose a significant threat, but a closer look may be necessary.

Possible countermeasures:

- Different blower configurations could help the air flow over the fins more efficiently thereby cooling them better.
- Record bolt temperature data and model with actual temperatures to decide whether or not this is an issue.
- Furthermore, more contact pressure can be applied to the thermoelectrics as specified by the manufacturer. The bolts have yet to be torued to specification.

Model Predictions vs. Test Results

Steady State Data			
Airstream Properties			
T in (K)	T out(K)	Mass Flow (kg/s)	Pressure Drop (Pa)
543	480	0.04	421
Cold Temperatures			
T_c (K) right front	T_c (K) right rear	T_c (K) left front	T_c (K) left rear
346	348	347	347
Hot Temperatures			
T_h (K) right front	T_h (K) right rear	T_h (K) left front	T_h (K) left rear
453	414	454	416

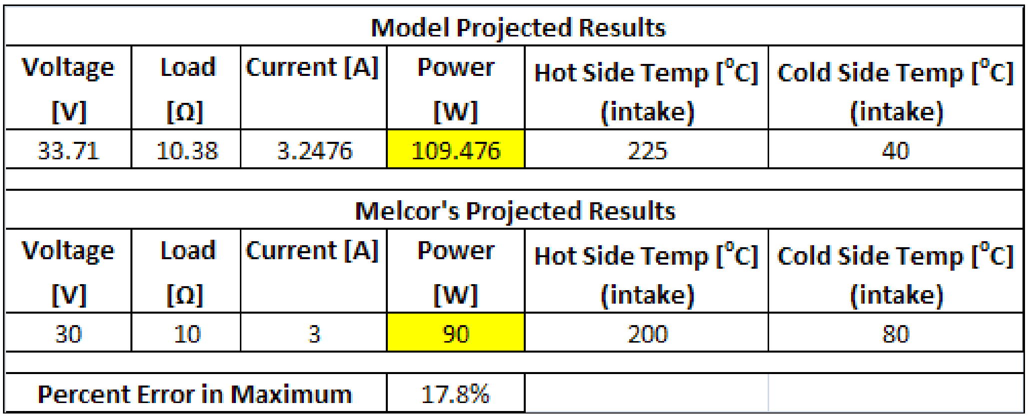
Model Predictions			
Airstream Properties			
T in (K)	T out(K)	Mass Flow (kg/s)	Pressure Drop (Pa)
550	438	.04	221
Cold Temperatures		**Hot Temperatures**	
T_c (K) right front	T_c (K) right rear	T_h (K) right front	T_h (K) right rear
350	330	508	424

Possible Reasons for Discrepancies

- Bad information from Aavid Thermalloy concerning the thermal resistance of extruded fins
- Uneven airflow over external fins
- Internal flow separation due to diffuser?
- Thermal adhesive curing

Electrical Issues Summary:

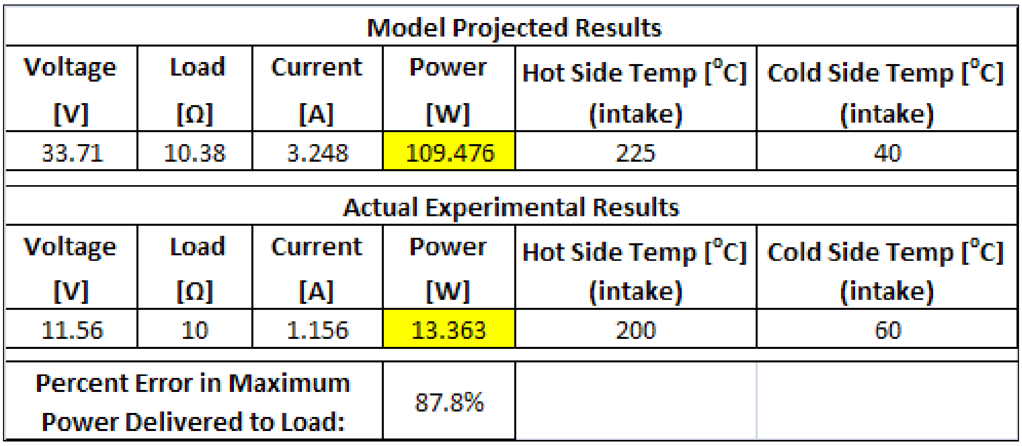
This project's objective is to recover wasted heat from an exhaust system and transform that into useable electrical energy. The end goal is to produce 100W and to be able to use a portion of that to charge a car's battery, thus taking some of the load off the alternator. The projected output from Melcor's given data is compared to the model's output in Table 1. It should be noted that the hot and cold side temperatures are different for each set of results, partially explaining the difference in output power.



Model Projected Results					
Voltage [V]	Load [Ω]	Current [A]	Power [W]	Hot Side Temp [°C] (intake)	Cold Side Temp [°C] (intake)
33.71	10.38	3.2476	109.476	225	40
Melcor's Projected Results					
Voltage [V]	Load [Ω]	Current [A]	Power [W]	Hot Side Temp [°C] (intake)	Cold Side Temp [°C] (intake)
30	10	3	90	200	80
Percent Error in Maximum			17.8%		

Table 1. Melcor vs. Model Results

The system was tested for the first time on Monday May 5, 2008. The table 2 summarizes the results for maximum power, and compares them to the expected, simulated values.



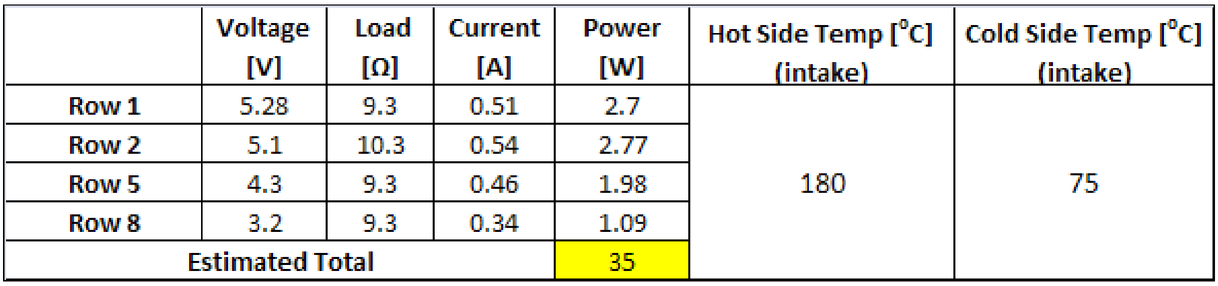
Model Projected Results					
Voltage [V]	Load [Ω]	Current [A]	Power [W]	Hot Side Temp [°C] (intake)	Cold Side Temp [°C] (intake)
33.71	10.38	3.248	109.476	225	40
Actual Experimental Results					
Voltage [V]	Load [Ω]	Current [A]	Power [W]	Hot Side Temp [°C] (intake)	Cold Side Temp [°C] (intake)
11.56	10	1.156	13.363	200	60
Percent Error in Maximum Power Delivered to Load:			87.8%		

Table 2. Results from Test 1

Wednesday, May 7, 2008, the model was tested for a second time. Modifications were made to improve results from test 1. Upon removing the heat sinks, it was noted that one of the TE solder connections was disconnected. This was re-soldered and each connection was verified to make sure there was continuity throughout. The RTV that was surrounding the TE's was replaced with fiber insulations in an attempt to force more heat through the TE's.

Thermal paste was added to both the TE's and the heat sinks to increase thermal contact. The TE configuration was modified to allow for measurements of 3 TE's in series to determine each row’s approximate output power capabilities. This enabled us to better match the load, and to avoid problems resulting from reverse current due to the parallel connections.

Table 3 summarizes the results from the second test. Select rows of three TE’s were measured and these results were used to extrapolate an estimated total power.



	Voltage [V]	Load [Ω]	Current [A]	Power [W]	Hot Side Temp [°C] (intake)	Cold Side Temp [°C] (intake)
Row 1	5.28	9.3	0.51	2.7	180	75
Row 2	5.1	10.3	0.54	2.77		
Row 5	4.3	9.3	0.46	1.98		
Row 8	3.2	9.3	0.34	1.09		
Estimated Total				35		

Table 3. Results from Test 2

Some of the losses not accounted for in the original modeling are listed below:

- Resistance associated with each wire used. There were approximately 48 wires, each with a nominal voltage drop. While individually small, the large quantity of wires could lend itself to a substantial voltage drop.
- When connection TE’s in parallel it is vital to have the same potential on each branch. This was known going in, and we took this into account when designing for the TE configuration, although not being able to match each voltage perfectly. Through testing it is speculated that the reverse current resulting from different potentials connected in parallel lead to significant loss of power.

To resolve the above issues, the following design improvements could be incorporated:

- Using less resistive wire to when connecting the TE’s will improve the output voltage delivered to the load, and thus increases the output power.
- Connecting diodes to the end of each branch before connecting them in parallel will force the current to the load, rather than splitting between the load and the TE’s that are at a lower potential.
- Using a TE configuration that puts all the thermoelectric modules in series would eliminate the problem of reverse current. However, this would require a large matched load, and the current would be significantly smaller.

The battery charging circuit was first built and tested Friday April 18, 2008. The output voltage was fluctuating slightly and was lower than we had designed for. While troubleshooting the circuit, it was discovered that the gate voltage of the MOSFET was significantly smaller than expected. This implies that the lead from the voltage regulating chip was too long and it is necessary to move the MOSFET closer to the chip, minimizing the line impedance. Other key components should also be located closer to the chip to improve functionality. The implementation of these design changes has been suspended until the more pertinent issue of power generation is resolved.

Future Improvement Lessons Learned:

- The thermoelectric pockets on the upper surface of the top plate are not integral to design. They do help position the thermoelectric consistently but add to the manufacturing process.
- Apply generous amounts of thermal paste to any contact surface. Originally it did not appear that the thermal paste was in contact with all the thermoelectric, which would reduce the system's ability to transfer heat.
- The factor of safety, or rather the overbuilding required to attain the specified performance was under estimated. Using the data at hand its clear that more dramatic cooling effects are needed. This could be manifested in a 'larger' cooling side fin structure.
- Troubleshooting time and refinement on the fly. While the scope and timetable of this project has remained fairly true to the project package, it has become apparent that laboratory troubleshooting and refinement contributed to significant performance gains. In addition to the performance gains, the laboratory test sessions have certainly provided an avenue of learning that is alternative to the generation of the thermal model.
- Testing has proved to be a significant way to mitigate potential risk in hardware damage. Laboratory experiments have resulted in the ability to run closer to the 'danger' zone of the particular modules in question, thus enabling higher overall performance.
- The cumulative nature of assumptions and unquantifiable inefficiencies has contributed to some short comings in the system performance. Perhaps more assumptions could be integrated in the mathematical model to at least augment the inherent deviation from ideal.