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A Multi-Year Thermoelectric Energy Harvesting Project for First-Year Engineering and Technology Students

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Abstract

Energy harvesting for continuously powering sensor networks is an emerging technology with tremendous potential. This paper is a report on progress made with involving first-year engineering and engineering technology students with thermoelectric energy harvesting research and prototype development that has occurred over several years. Each year, the student group built upon the work of the previous year's group. Expectations for each team were kept realistic such that the goals were attainable. However, each group was required to present their work at a regional undergraduate research conference. During the first year of the project, thermoelectric generator (TEG) devices were characterized and tested. The students designed and constructed test fixtures for the TEG and conducted performance tests. Mathematical models were developed and compared with actual TEG performance. During the second year, another group of first-year students designed and constructed circuitry to boost the relatively small TEG output voltage to a level more useful for powering conventional (3.3V or 5V) electronic devices. The boosted output voltage was used to power all of the circuitry thus a self-sustaining system was produced. Sensors and circuits were added to measure the TEG system temperatures and transmit them to a computer for display. The third year's group identified a hot water pipe within the engineering building that could serve as a heat source from which a TEG could be powered. A laboratory mockup of the water pipe heat source was constructed such that it could be tested prior to actual installation. The group designed and fabricated a pipe-to-TEG heat exchanger and custom TEG-to-air heat sink for the cool side of the device. The performance of the system was tested using hot water input temperatures that will be experienced in the actual installation. This paper presents details of each group's work as well as observations of student motivation in performing undergraduate research.

Introduction

First-year engineering and engineering technology students at Penn State - Berks have the opportunity to get involved with current research being conducted by engineering faculty.[1] Through this experience, the students are exposed to concepts and methods that might otherwise be delayed for later semesters of study, if encountered at all. In the experience presented here, the students explored the concept and use of a thermoelectric generator (TEG) as an energy harvesting device. The work spans three years and three separate student teams. Each year, the team built upon the work performed by the previous year's team. Each team also presented their portion of the work at a local undergraduate student research conference.

Energy harvesting (which may also be called *energy scavenging*) is the process of capturing forms of energy that might otherwise be neglected or wasted for the purpose of powering electronic systems. This type of energy capturing is particularly useful in systems where the power demand or duty ratio is small. The energy source being studied here is residual or waste heat.

Thermoelectric generators have become very attractive low-power energy harvesters for powering applications such as industrial and automotive sensor networks.[2] A TEG is a solid state device that uses the same principles as thermocouples to generate electricity from a temperature difference between two surfaces.[3] Temperature differences as small as 5°C can be used to produce a useful amount of energy. Figure 1 shows a hybrid thermal and electrical diagram of a thermoelectric device. Figure 2 shows a photograph of the actual TEG used by the students.[4]

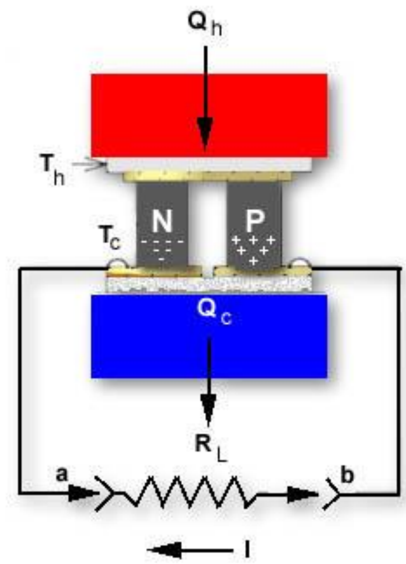


Figure 1. Thermal / electric energy flow diagram of TEG device (*Ferrotec*)

Figure 2. TEG used by students. (Actual size is 1.2” x 1.3” x 0.14”) (*Marlow*)

The goals for each year's team were set high enough to encourage them to work hard, but yet low enough not to discourage them from trying. Because the students were first-semester freshmen, they were entering the project relying on experience obtained prior to college. Some students have a good deal of hands-on tinkering experience while others had none. The team met with the instructor once each week for status reporting and problem resolution. With the help of the electrical laboratory and machine shop managers, the students were able to produce very high quality test setups and fixtures which produced very good test results.

TEG Project, Year One

The first year of the TEG project began with no test fixtures and a few TEG samples from Marlow Industries (which were actually marketed as thermoelectric coolers). The challenge for the team of four freshmen students was to construct a test fixture which could reliably produce hot and cold surfaces and obtain electrical data to characterize the performance of the TEG units.

The members of the team with CAD experience designed an aluminum plate to which large power resistors could be mounted to produce the hot side for the TEG. The plate included tapped holes for mounting the resistors, clearance holes for bolts which would clamp the TEG assembly together, and a tapped hole for mounting a small temperature sensor (thermocouple).

The cold side of the TEG test fixture was produced with finned aluminum heat sink material leftover from a previous department project. The heat sink material had to be cut and machined to provide clearance holes for the TEG assembly clamping bolts and a tapped hole to receive the cold-side temperature sensor (thermocouple).

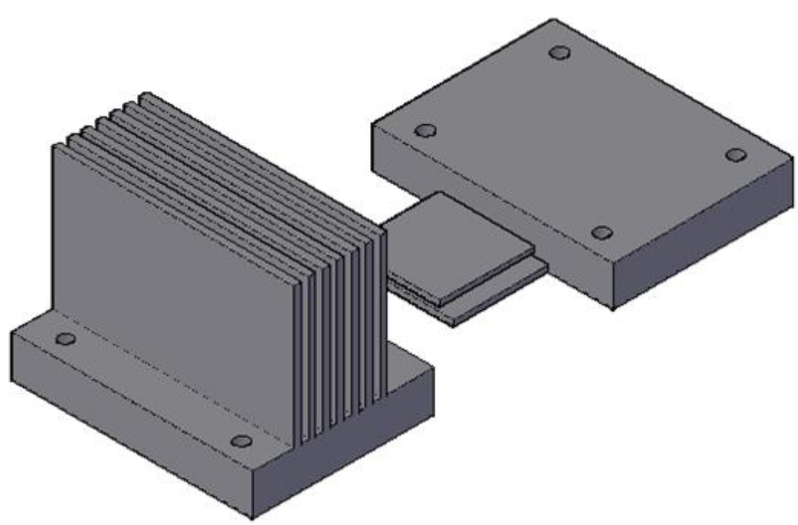


Figure 3. SolidWorks Design for TEG Test Fixture (*Phillip Pezzopane*)

Figure 3 shows the SolidWorks design of the hot and cold surfaces for the TEG test fixture. The team worked together with the campus machine shop manager to modify the design such that a more easily produced fixture was created. Figure 4 shows the thermal test fixture connected into the final test setup. The team experimented with various combinations of power resistor current and cooling fan orientation to obtain repeatable and stable thermal conditions in which to tests the TEG.

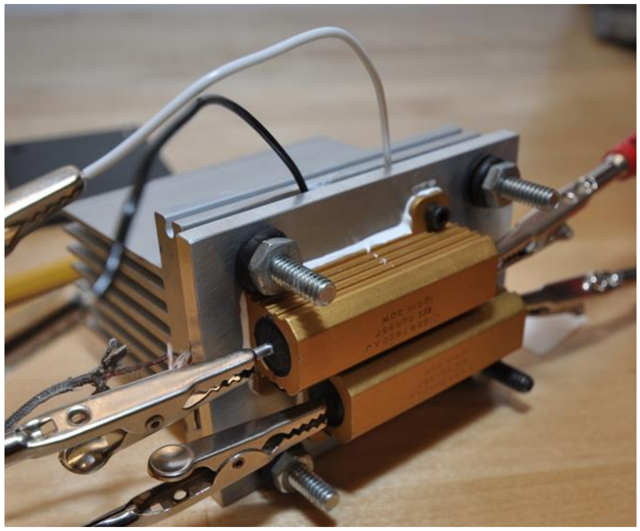


Figure 4. TEG Thermal Test Fixture (*Byron Dinas*)

With the mechanical / thermal test fixture complete, the students constructed the electrical test setup and obtained data to characterize the performance of the TEG. The students were introduced to LabVIEW and, using some electronic hardware constructed for another project, were able to devise a computer-controlled load to obtain output data for the TEG. Figure 5 shows a photograph of the complete bench test setup. Performance data is shown in Figures 6 and 7.

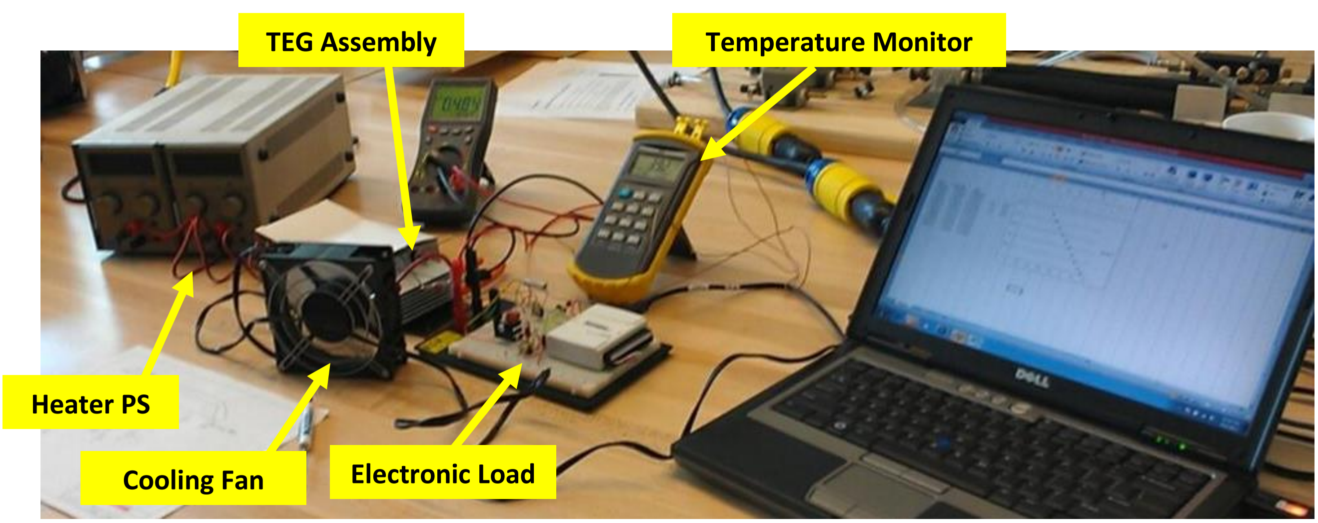


Figure 5. TEG Project Year One Test Setup

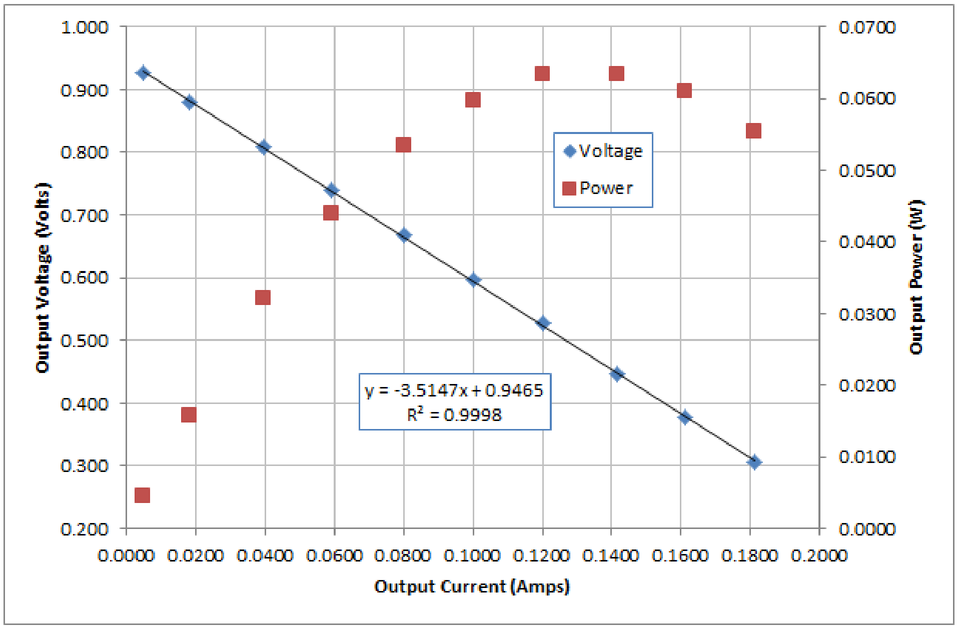


Figure 6. TEG Performance Data for ΔT = 21.8°C

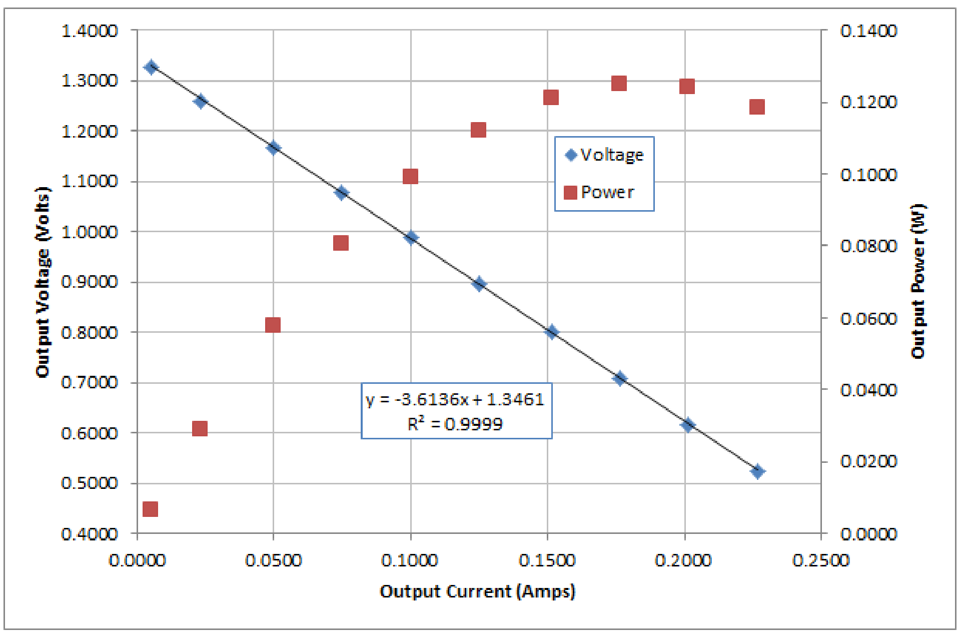


Figure 7. TEG Performance Data for ΔT = 30.8°C

Based on the data shown in Figures 6 and 7, the students were able to determine the simplified electrical model parameters as shown in Table 1. The simplified electrical circuit model, the Thévenin equivalent source, is shown in Figure 8.

Table 1. TEG Performance Data

$\Delta T = 21.8°C$	$\Delta T = 30.8°C$
$V_{TEG} = 0.947V$	$V_{TEG} = 1.350V$
$R_{TEG} = 3.51\Omega$	$R_{TEG} = 3.61\Omega$

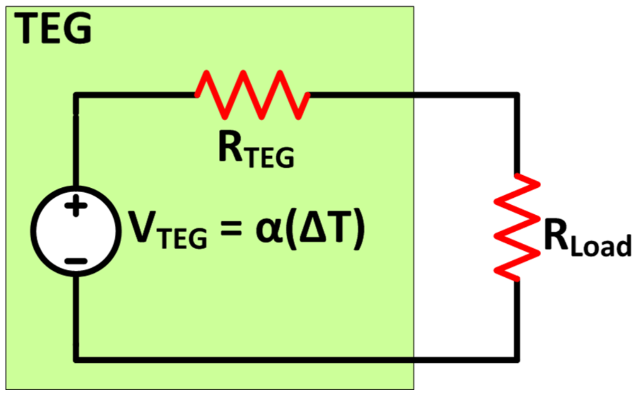


Figure 8. Simplified TEG Electrical Circuit Model

TEG Project, Year Two

The challenge for the second year's team of students was to develop a circuit to boost the output voltage of the TEG to a level more useful by conventional electronic circuits. Their goal was to build a boost converter circuit that could be completely self-powered, including a way to transmit TEG temperature and voltage data to a PC for display and/or logging. Once again, the experience of the team members was very limited but they were willing to try almost anything.

Data from the first team's research indicated that the TEG output voltage was around 1V and had a source impedance of about 3.5Ω for temperature differences near 20°C. Although there exists commercially available components for TEG output boost converter circuits,[5] the team was encouraged to explore more conventional techniques.[6]

To learn about the concepts of boost DC-DC converters, the students built a simple circuit that would allow for experimentation with various operating frequencies and duty ratios without the need for an actual TEG assembly. Figure 9 shows a schematic of the circuit. The power supply and the parallel combination of three 11Ω resistors were used to emulate the TEG equivalent output circuit. With this circuit, the students found that a switching frequency of about 10kHz with a duty ratio of about 92% was needed to produce an output voltage, Vout, of about 6V with an output current of about 5mA which would be more than enough to self-power the circuit.

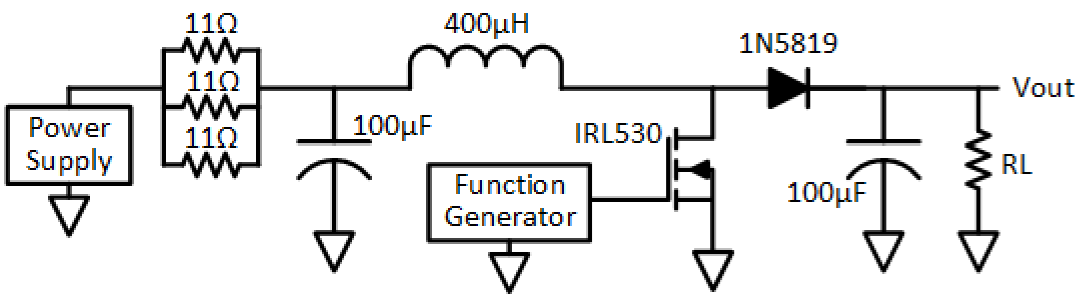


Figure 9. Boost Converter Experimentation Circuit

Using hardware from another project, the students built and tested a boost DC-DC converter using a PIC microcontroller to produce the required switching frequency and duty ratio. The boost converter was measured to have an efficiency of 81% at typical input and output conditions. The PIC could also be used to make the desired system voltage and temperature measurements and transmit them serially to a PC. A 5V linear regulator, LM2936,[7] was used to provide a more stable and precise supply voltage for the microcontroller. The TEG hot and cold side temperatures were measured by using electronic temperature sensors, LM34CZ,[8] embedded in the aluminum test fixture. These sensors replaced the thermocouples installed by the first year team. Figure 10 shows a block diagram/schematic of the complete TEG system. Figure 11 shows a photograph of the actual system. A screen shot of the LabVIEW front panel used to display the data transmitted from the PIC microcontroller is shown in Figure 12.

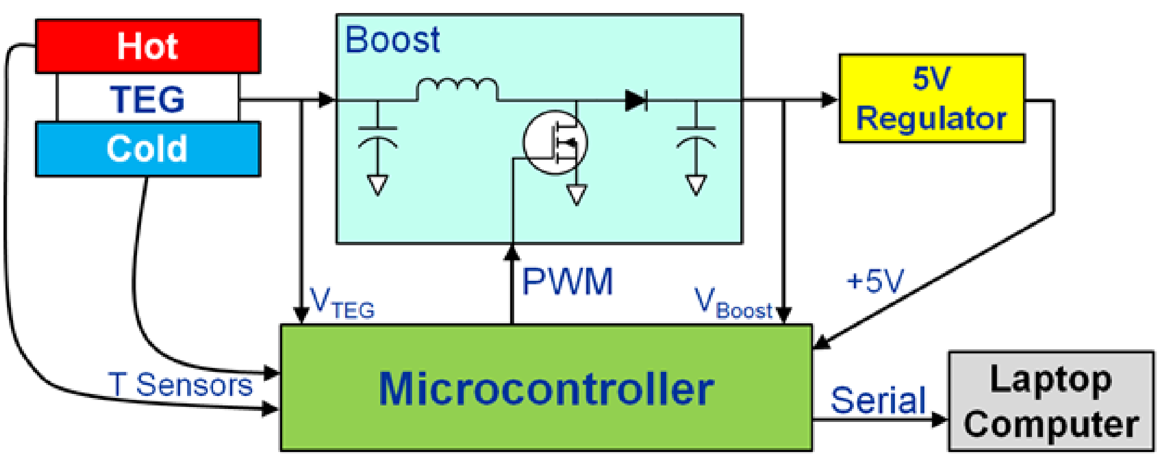


Figure 10. TEG Energy Harvesting System Diagram

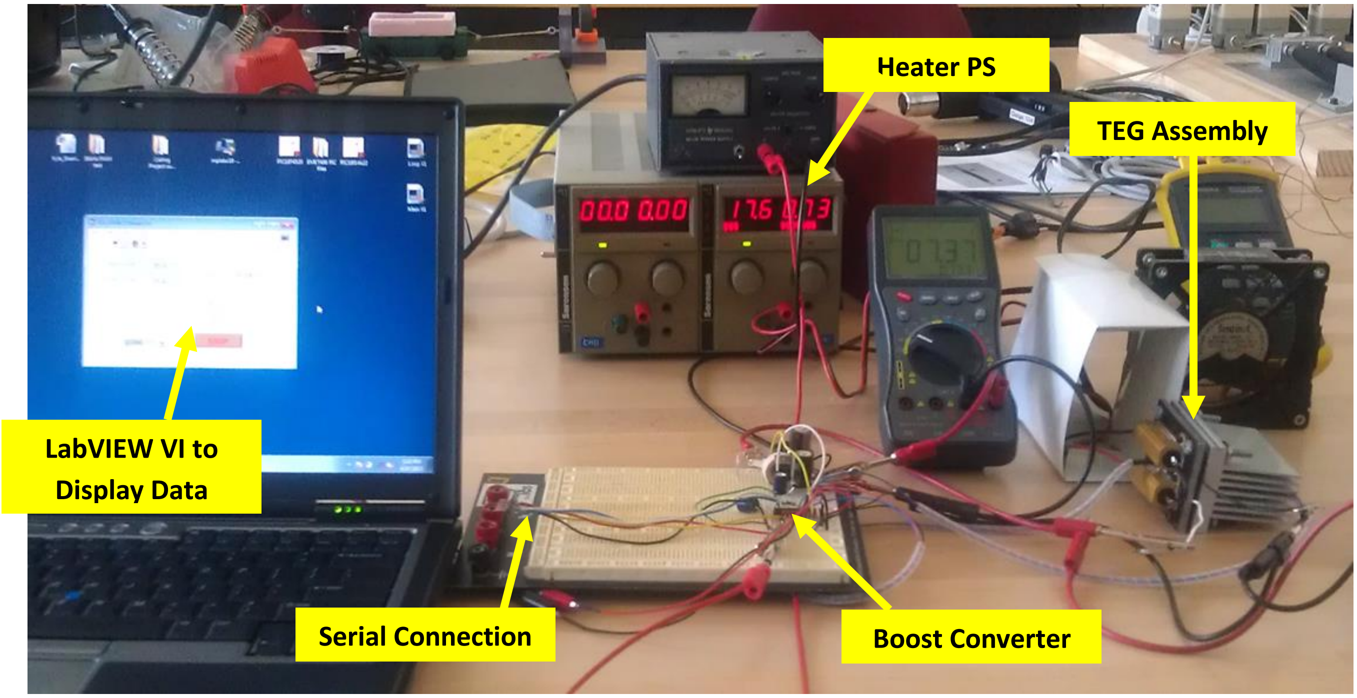


Figure 11. Actual TEG System Setup

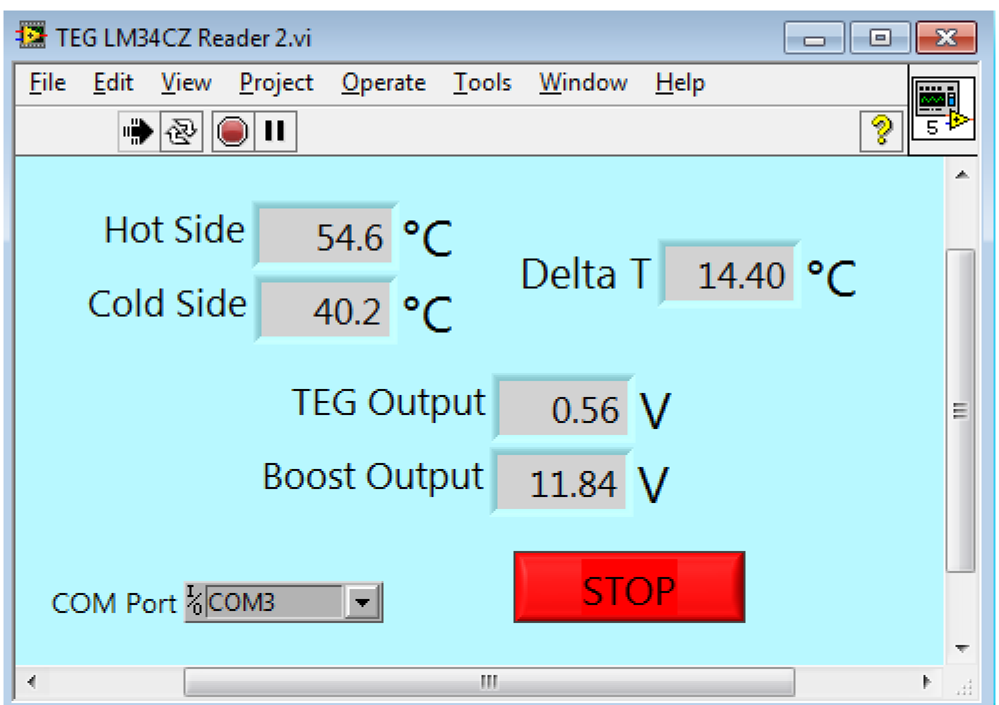


Figure 12. Screen Capture of LabVIEW Front Panel to Display TEG Data

TEG Project, Year Three

In the third year of the project, the students were asked to identify a location within the engineering building which might provide a constant source of waste heat to be used as the energy source for the TEG. Implementing energy harvesting hardware in the field introduces many practical problems that must be solved.[9] After meeting with the HVAC maintenance technician, a potentially useful heat source was found in the utility room. The building heating system consists of a pair of natural gas fired boilers and circulating pumps that operate alternately for redundancy and to provide for scheduled maintenance on the non-operating boiler and pump. The output of the two pumps is combined to feed one continuous hot water loop that circulates throughout the building. In the winter, the water temperature set point is about 180°F (82°C) while in the summer it is about 130°F (54°C). The students planned to attach the TEG to a small pipe that is tapped into the main circulation loop.

The small pipe that would serve as the heat source was found to be a standard 3/8 inch inside diameter "black pipe." The team used their combined limited CAD experience to design a fixture that could be clamped onto a 3/8 inch pipe. The heat sink (cold side) design from the previous years was slightly modified to make it more compact to fit the installation space. Figure 11 shows the SolidWorks design of the TEG hot side and cold side clamping components.

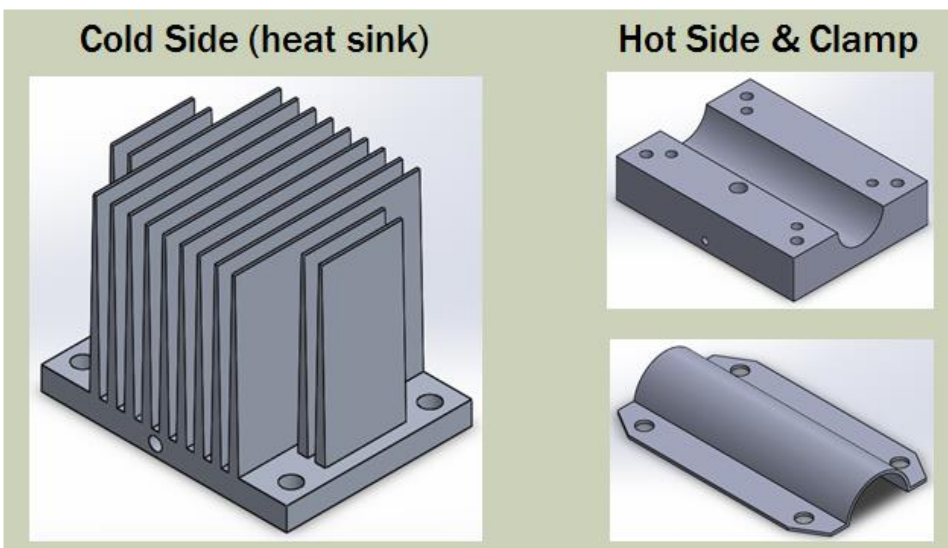


Figure 11. TEG Components for Attaching to Hot Water Pipe (*Nathan Kimmel*)

The students also designed a test setup that would produce hot water and contain a section of 3/8 inch black pipe through which the hot water would continually flow. The TEG operation could then be tested prior to installation in the utility room. Figure 12 shows a photograph of the hot water heater and circulator test setup.

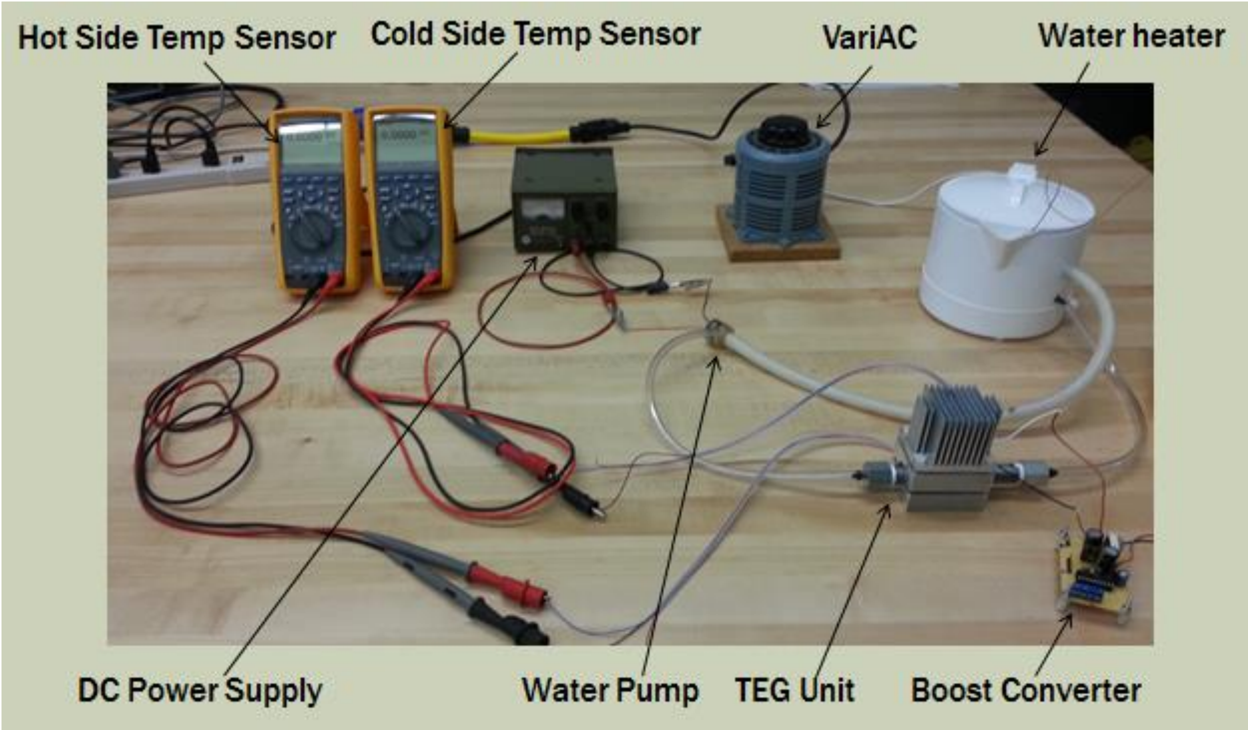
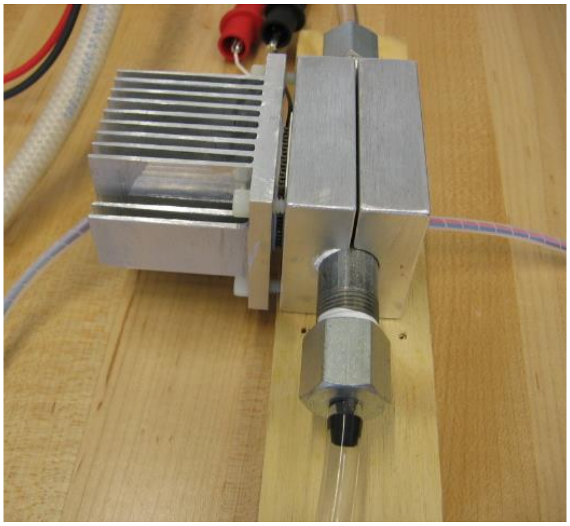


Figure 12. Hot Water Heater and Circulator Test Setup

One of the members of the “year two” team volunteered to continue with their part of the project by building the boost converter circuit in a more permanent fashion. The student constructed the circuit on a rigid “perf board” with soldered connections on the back side. This circuit can be seen in the lower right corner of Figure 12. The student also packaged the circuit in a plastic box such that it could be mounted near the TEG unit at the final installation site.



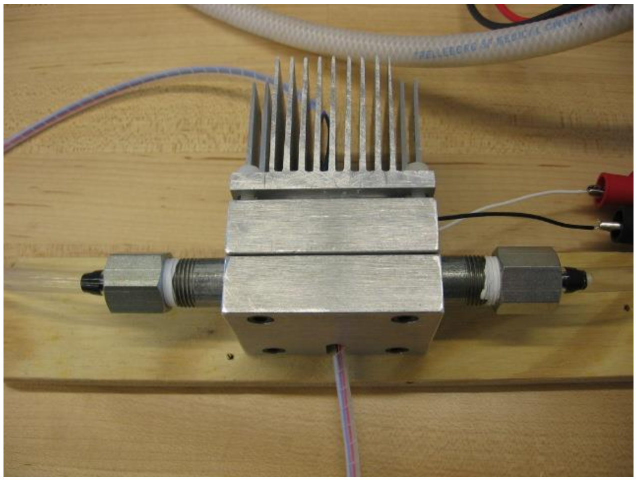


Figure 13. Photos of TEG in Hot Water Test Setup

Close up photographs of the TEG assembly attached to the section of hot water pipe in the test setup are shown in Figure 13. Using the hot water test setup, the students successfully demonstrated the operation of the TEG with their heat exchanger design. The temperature of the hot pot water was measured with a thermocouple. The water temperature was adjusted via the Variac which controlled the input voltage to the hot pot. Data from the setup is shown in Table 2.

Table 2. Hot Water Test Setup Data

Hot Pot Outlet Water Temperature	TEG Hot Side Temperature	TEG Cold Side Temperature	TEG Output Voltage	Variac Setting
147°F (63.9°C)	138°F (58.9°C)	104°F (40°C)	0.987V	35%
143°F (61.7°C)	136°F (57.8°C)	109°F (42.8°C)	0.771V	31%
142°F (61.1°C)	134°F (56.7°C)	110°F (43.3°C)	0.716V	30%

The third year team was unable to mount the TEG energy harvesting system in the utility room as planned. The pipe that had been identified as a possible candidate for attaching the TEG unit was not useable. The pipe did not contain a constant flow of the building heating water as originally thought and therefore would not have been a reliable source of heat. Further investigation for another heat source is now necessary.

Conclusions

First semester freshman engineering and engineering technology students are more than eager to dive in and do something that resembles "engineering." Keeping this level of motivation as the semester wears on, is another challenge. However, with regularly scheduled meetings, project progress can be made and good results can be achieved.

The students each had to rely on previous experience at the beginning of each phase. They each gravitated toward the aspect of the work that most interested them. As the semester progressed, there appeared to be more crossover of abilities and sharing of knowledge among the group. As the deadline for presentation of results neared, the level of activity also ramped up.

Each fall, the students were new to the project so the sense of continuation was only perceived by the faculty and staff involved. However, once the students became familiar with the project direction, they too showed a good level of commitment to making it happen. The project itself could never have been fully completed in one semester but by breaking it into smaller pieces and being patient with the long pauses in progress, a bigger payoff could be realized.

By the end of the third year the TEG was not yet installed in the physical plant system, however, all of the components are tested and ready. Perhaps that will be the task of the fourth year's team.

Acknowledgements

The author would like to thank the members of all the student teams for their commitment to the project. Special thanks to the machine shop supervisor, Mr. Roy Thompson, for his technical assistance and labor to help produce the parts necessary for this project.

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