COVER PAGE

Title of Design: **Developing Energy Harvesting Prototypes to Generate Electricity from Runway Pavement Infrastructures of Airports**

Design Challenge Addressed: **Airport Environmental Interactions**

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Executive Summery

This study aims at developing a thermoelectric energy harvesting prototype for runway pavement infrastructure in the airports that can be served as alternate energy sources. The power can be stored in a built-in battery and can be a supplement to energy need for runway signage, signaling and communication during blackout in the airport as well as meet the energy demand for remote airports that don't have access to grid electrical power. This is an emerging research field which encompasses technologies that capture the existing thermal energy in runway pavements to generate electricity without depleting natural resources. In lower latitudes, such as Texas, the runway surface temperature in the summer rises as high as 55°C due to solar radiation. Soil temperatures below the pavement, however are roughly constant (i.e. 27°C to 33°C) at relatively shallow depths (20 cm). This thermal gradient between the surface temperature and the pavement substrata can be used to generate electrical power through thermoelectric generators (TEGs) modules. The proposed prototype collects heat energy from the runway pavement surface due to solar radiation and transfers it to a TEG module embedded into the subgrade at the edge of the pavement shoulder. Evaluation of this prototype was carried out through finite element analysis, laboratory testing and field experiments. The results suggest that the 6.4cm x 6.4cm TEG prototype can generate an average of 12 mW of electric power continuously over a period of 8 hours, for the weather conditions encountered in Texas. Scaling up this prototype using multiple thermoelectric elements could generate sufficient electricity for sustainably power backup for LED lights signage in the runway, low-cost continuous sensing and communication technologies to collect runway structure conditions.

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1.0 Problem Statement and Background

The air transportation infrastructure serves a critical societal need to move rapidly goods and people across the nation. Using these infrastructure as a source of renewable energy by harvesting it from the runway is a novel idea that has not been fully explored yet. The proposed technology is aimed at revolutionizing our vision towards integrating runway infrastructure into a continuous, efficient means for harvesting usable energy.

One of the emerging technology for sustainable energy harvesting is using thermoelectric generators. A Thermoelectric generator (TEG) is a solid-state device that converts heat (temperature differences) directly into electrical energy. Asphalt pavement runways are ideally suited for installing such technology because they are readily heated during the day. The system collects energy from the temperature difference between the pavement surface and the subsurface roadside soil. This energy harvesting strategy can potentially be used to store energy for future use.

The primary goal of this research is to design and develop a novel thermoelectricity generation prototype to harvest low-cost clean energy from airport runway infrastructure and to develop instrumentation that use this harvested energy to address the following issues;

- Sensing excursion on runways being installed along the edges or at the runway entrances. The system can pick up the wheel load difference of airplane and a vehicle. And warn airport controller of the incident immediately.
- Sensing airplanes wheel load, speed, etc. to assist in pavement management and maintenance and monitoring pavement performance (stress reduction, moisture, temperature, etc.)

- Alternative energy source for runway signage, signaling and communication during blackout in the airport
- Supplement the energy demand for remote airports that don't have access to grid electrical power.

The objectives of this research are:

1. Conducting literature review on means of harvesting energy from runway pavement infrastructure.
2. Using Finite Element analysis to evaluate harvester prototypes designs to maximize harvesting energy from pavement structure in runways and taxiways.
3. Laboratory testing of an in-house fabricated harvester prototype to estimate output power.
4. Demonstrating the prototypes performance through installation in pavement structure and data collection.
5. Studying the economic benefits for implementing as well as integration of this technology as alternative energy-producing and energy-saving technology into the airport environment.

2. Summary of Literature Review

Sustainable source of energy is one of the great challenges in generating clean power. There are several energy sources available for this purpose, such as photovoltaic, wind and geothermal. An emerging technology for sustainable energy harvesting is thermoelectricity, whereby temperature gradients in a structure are used to directly power thermoelectric generators (TEGs).

Asphalt pavements runway are ideally suited for installing such technology because they readily heat up during the day. In southern states, it varies from 45 to 55°C (fig 3.1).

The concept of energy conservation and the need for developing alternative energy resources has become pressing due to the environmental impact of fossil fuels. The massive generation of greenhouse gases is interrupting the climate balance and the non-renewable conventional energy resources are being depleted. Moreover, seeking non-traditional low-cost energy resources becomes increasingly necessary *(1).* Energy harvesting (scavenging) is a process that captures unused ambient energy that would otherwise be lost in the form of heat, vibration, stress or deformation. Piezoelectric technology is recently introduced to harvest kinetic energy under moving traffic in roadways. The energy density is not high enough to compete with other proven photovoltaics energy harvesting technologies (2). Solar roadway is to use surface photovoltaic technology for harvesting solar energy. These technologies replace asphalt pavement materials with custom-made solar panels (3). Major concerns are their durability to resist traffic impact and preserving surface texture for the safety of motorists. Also, the effect of shading caused by obstructions from buildings, trees, cloudy conditions and from passing vehicles may impact the efficiency of solar roadways.

2.1 Energy Harvesting Using Thermal Gradient

The pavement surface absorbs sunlight energy and stores the energy in the form of heat. The temperature profile of a pavement changes along its structural layers in the manner that the surface temperature remains highest in the summer or in a sunny day and decreases going deeper into the soil. This generates a thermal gradient between surface and soil layers below. The thermal gradient can be used as input energy to generate electric power.

Some researchers *(4,5)* worked on laboratory simulation to take the advantage of the thermal gradient between the pavement surface and the soil. An electric circuit was designed to measure and store the output power (Fig. 2.1).

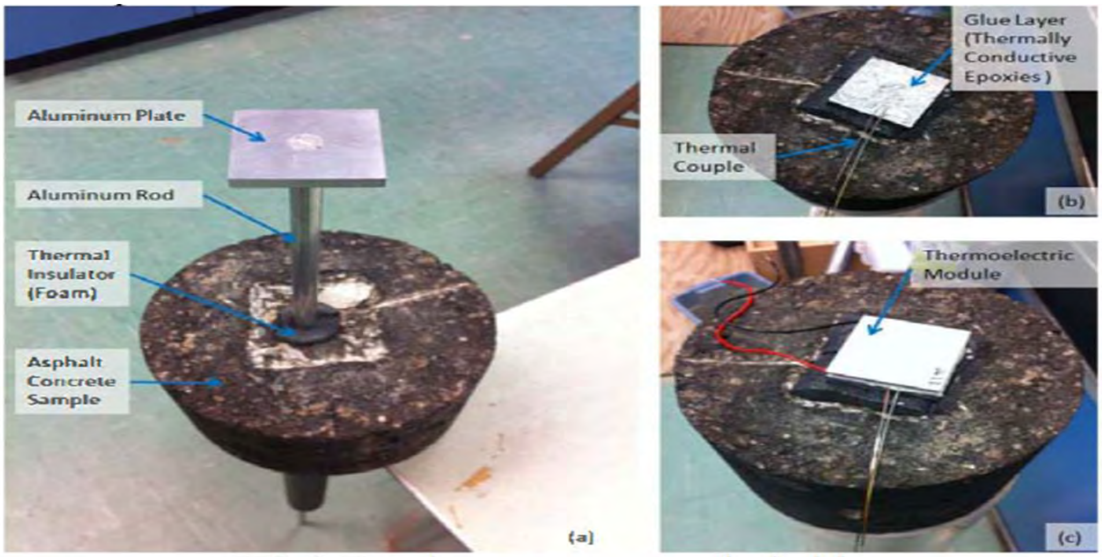


Figure 2.1: Experimental set up of thermoelectric energy harvester *(1)*

There is also other researches *(6)* on simulating temperature sensors at variable depth of pavement to study the possibility of thermal energy harvesting. They recorded temperature data with multiple thermal sensors and tried to measure the available thermal gradient along the depth (Figure 2.2).

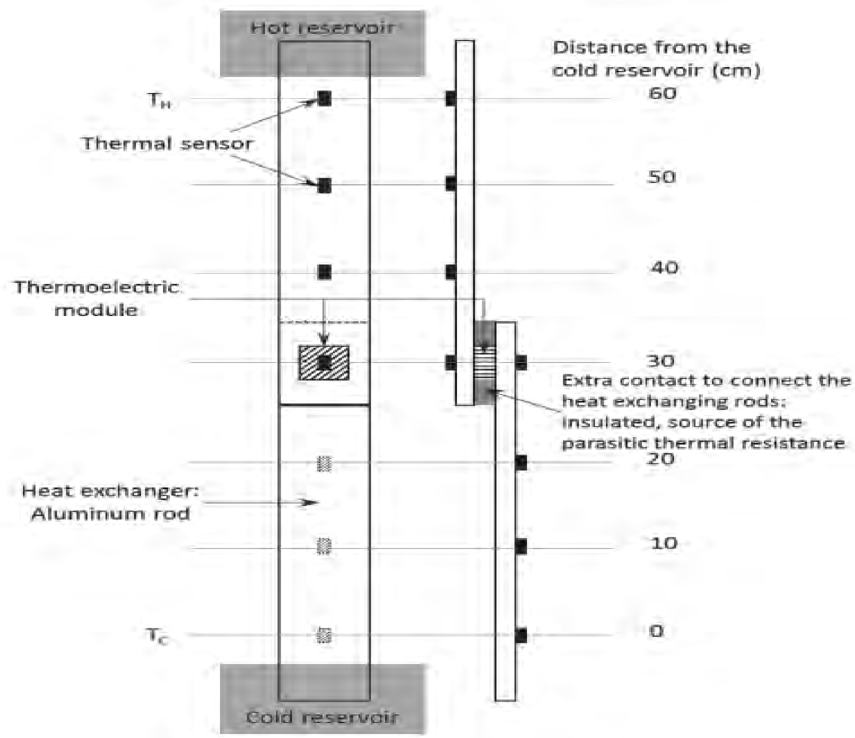


Figure 2.2: Thermal sensing along with depth from pavement surface *(5)*

Energy harvesting systems from temperature gradients within pavement is a novel concept. Limited literature describes efforts to develop such systems through computer simulations and laboratory testing *(7)*. One of the problems of these systems is the location of the thermoelectric element within the asphalt concrete layer. This exposes the TEGs to traffic hazards and compromises their longevity. This not only makes TEGs less accessible, but also weakens the pavement structure itself. Other limitations are the heat dissipation that inadvertently get conveyed across the TEG leading to a reduction in system efficiency over time. The key element for thermal energy harvesting from pavement is the TEG which absorbs the temperature gradient as input energy source and converts it into electrical energy.

3. Problem solving and design approach

3.1 Background

During the study the runway infrastructure data of San Antonio International Airport (SAT), Texas was considered. Considering the pavement cross-sectional properties as well as weather data *(5)* of the year 2010 for that particular monitoring station at SAT, pavement temperature profile of the runway was generated using TEMPS software (Figure 3.1)

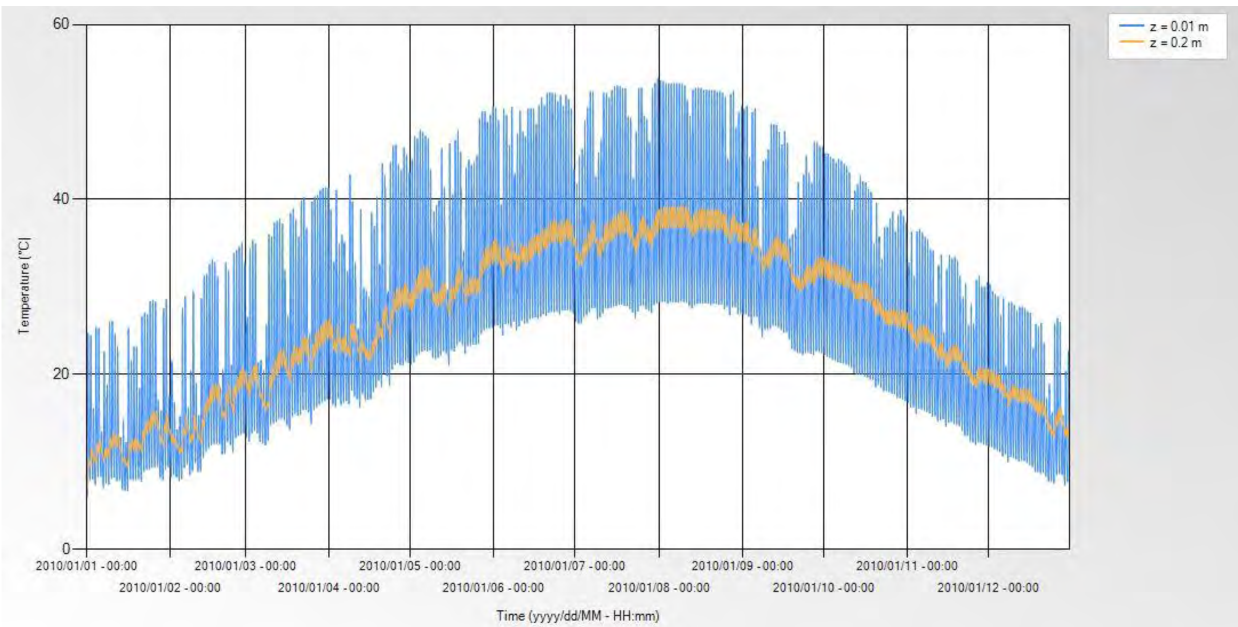


Figure 3.1: Runway temperature profile at San Antonio International Airport

Depending upon air temperature and sunlight throughout the year, pavement surface temperature at a depth of 1 cm varies from 40 to 55°C while the corresponding roadside soil temperature at a depth of 18 cm varies from 27 to 32°C throughout the year *(8)*. So, there is a clearly 18 to 23°C thermal gradient available (Figure 3.2) in between pavement and corresponding roadside soil which can be an ideal source for energy harvesting.

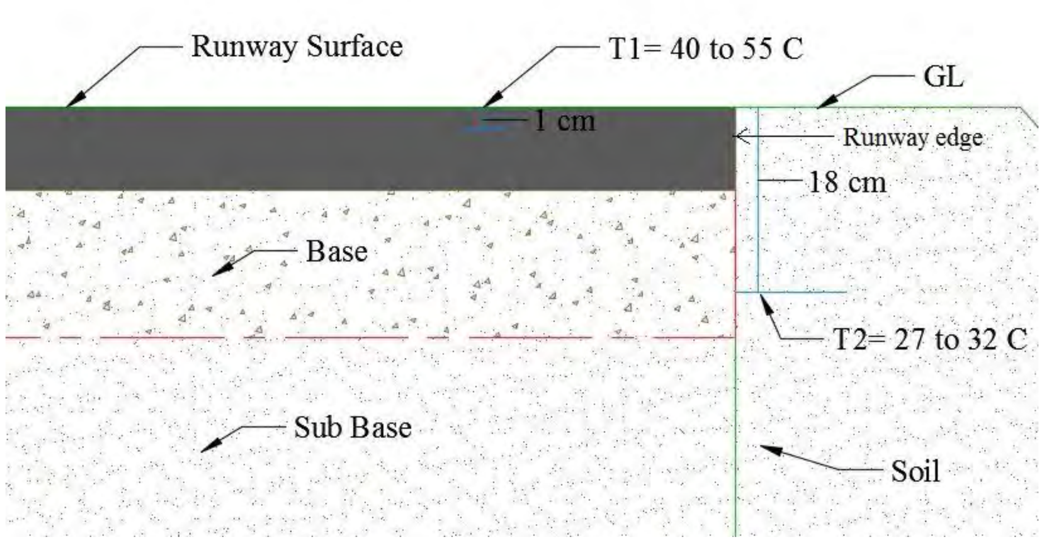


Figure 3.2 Pavement and soil temperature

In this chapter a thermal energy harvesting prototype will be developed to harvest thermal energy from the pavement surface using thermoelectric generator (TEG) which is placed into roadside soil to ensure adequate thermal gradient (Figure 3.3).

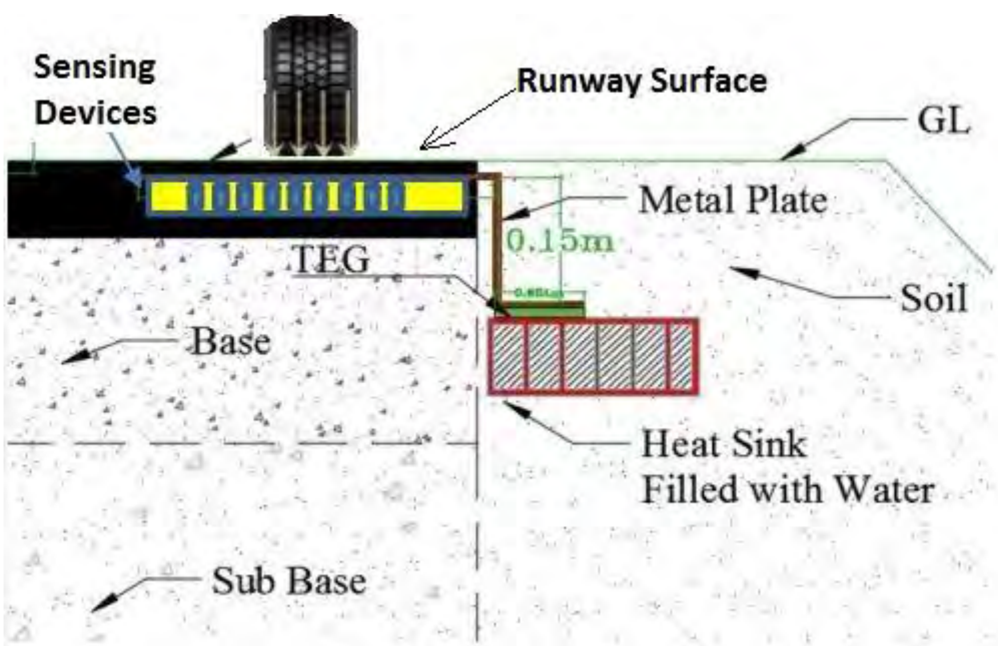


Figure 3.3: Energy harvesting prototype at runway edge

A “Z” shaped metal plate is an ideal tool that can harvest the energy from the pavement surface of the run way at its edge and transfer the collected heat at a certain depth into the roadside soil to maintain the required thermal gradient for operating the prototype (figure 3.3). The metal plate must have a proper insulation to ensure maximum heat supply to TEGs.

3.2 Prototype Description

The prototype consists of two basic components,

1. Heat energy harvester (i.e. thermal harvester) and
2. Thermoelectric generator

The thermal harvester provides significant and continuous temperature difference between top and bottom surface of the TEG. The temperature difference, or thermal gradient, (ΔT) ensures continuous heat transfer flow through the TEG that allows for the power production.

The prototype efficiency depends on the performance of the thermal harvester. The higher the temperature difference it ensures; the higher electrical power it produces. To maximize the prototype efficiency and power output, several simulations of thermal harvester dimensions were analyzed through finite element analysis as part of the early stage of this research. Finally form the results of finite element analysis an optimum model dimension was selected for laboratory and field testing.

3.3 Heat Energy Harvester

The thermal Harvester consists of two basic parts; heat conducting metal plate and heat sink as shown in Figure 3.4. The description and components of each part is as follows:

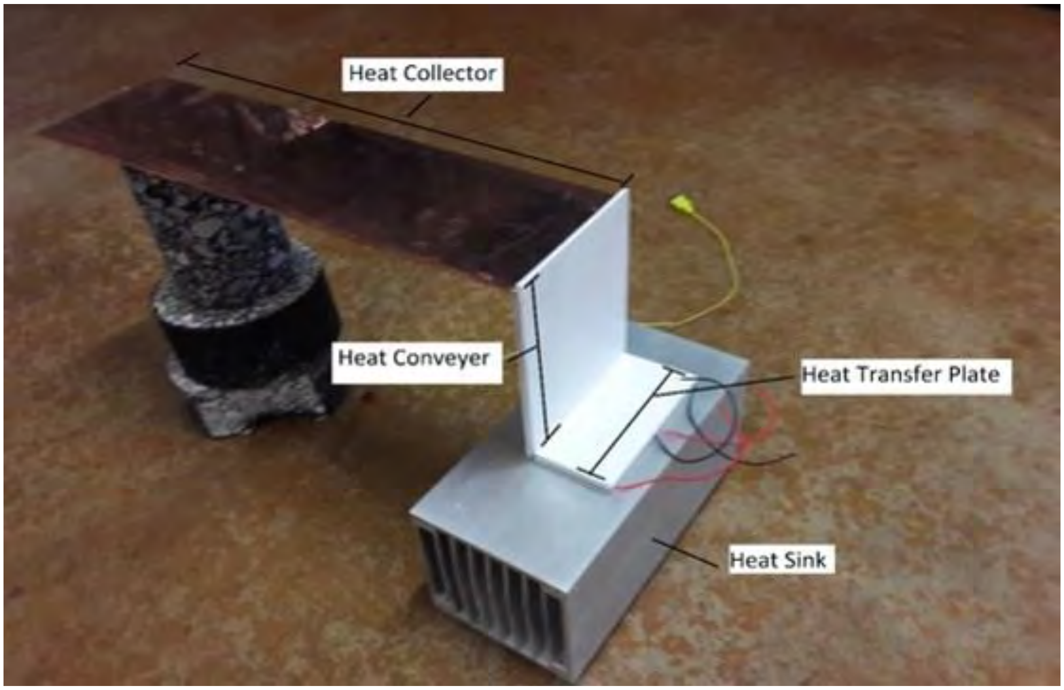


Figure 3.4: Heat energy harvester

3.3.1 Heat Conducting Metal Plate

The heat conducting metal plate is an elongated Z-shape plate with constant width (Fig. 3.5). The function of this part is to collect the heat energy from the pavement surface, convey the collected heat to certain designed depth and ultimately transfer the collected heat energy to the TEG. To harvest greater amount of energy, a highly thermo-conductive metal should be selected. In this research a copper plate was considered in the experimental setup. The heat conductive metal plate is segmented into three parts:

a) Heat collector
b) Heat conveyer
c) Heat Transfer Plate

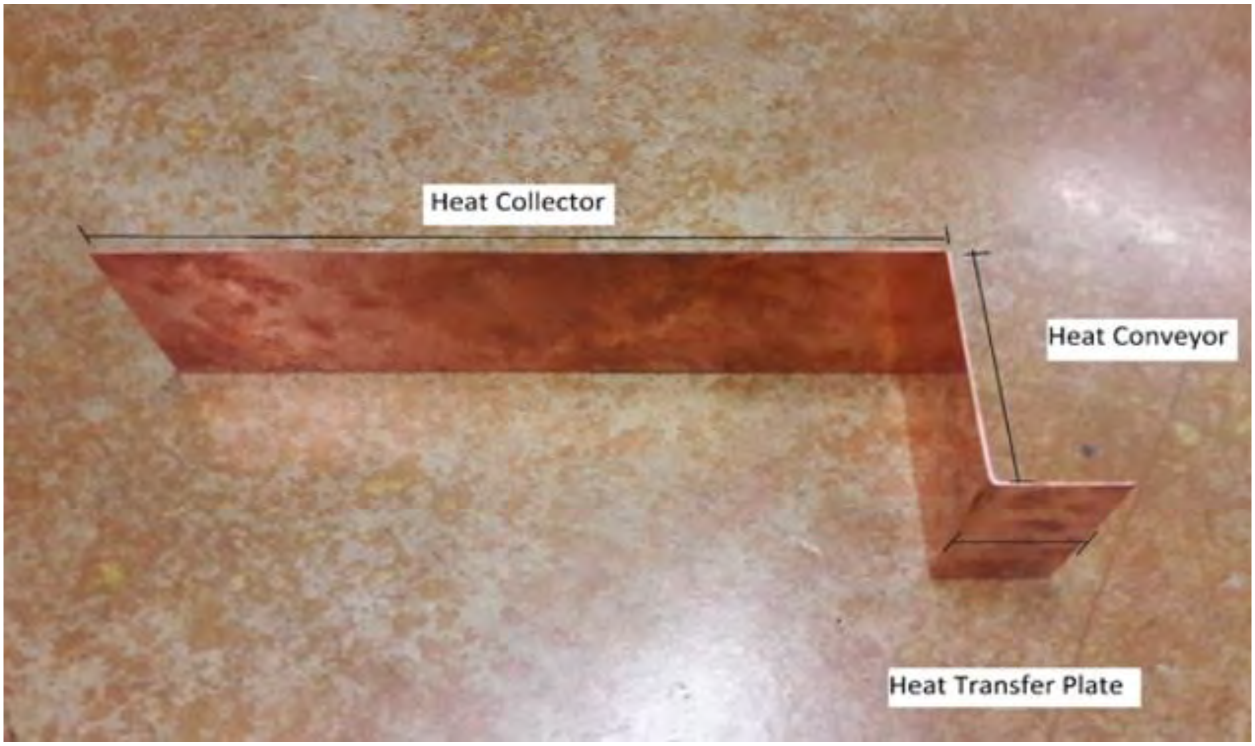


Figure 3.5: Heat conducting metal plate

a) Heat collector: Heat collector (Fig 3.5) is the longer part of the conducting plate, with a rectangular shape. This portion is inserted at shallow depth (i.e. 2cm from the top surface) of the pavement. The function of this segment is to harvest the surrounding heat flux from asphalt road surface and transfer it to a heat conveyer. Starting from the edge of the pavement shoulder this segment usually extends up to 45 cm into road surface. The design dimension of the heat collector depends upon the number of TEG to be used, pavement condition and serviceability. Clearly, increasing the surface area of the heat collected assists in increasing the heat transfer flow to the TEG ultimately increasing the power produced.

b) Heat conveyer: Heat conveyer is the flat vertical (drop-off) section of the conducting plate, and is usually rectangular. The conveyer transfers the heat flux from the heat collector towards the heat transfer plate in contact with the TEG. In fact, it is monolithic with the heat collector and heat transfer plate. This part of the conducting plate is inserted along the edge of the asphalt road surface to a depth of 16-18 cm in the surrounding soil. This segment must be properly insulated to preserve the heat flux from dissipating into the soil particles. In this experimental setup, the heat conveyer was wrapped by Poly Vinyl Chloride (PVC) sheets glued around the plate's faces with a thermal adhesive. Proper isolation and optimum depth dimension of the heat conveyer are important factors in the prototype design affecting the heat flux intensity at the TEG.

c) Heat Transfer plate: This part of the conductor plate directly transfers the heat flux into the TEG. The dimension of the transfer part is dependent on the size and numbers of TEG used in the experiment. For instance, using a set of two TEGs require a dimension of 6.4 cm x12.5 cm while using a set of four require a dimension of 4 cm x16 cm. The top surface of the heat transfer is covered by PVC sheets to avoid heat loss (Fig. 3.4). The bottom surface is glued with the TEGs using a highly conductive thermal paste.

3.3.2 Heat sink

A heat sink is a passive heat exchanger that transfers the heat generated by an electronic or a mechanical device to a fluid medium, often air or a liquid coolant, where it is dissipated away from the device, thereby allowing regulation of the device's temperature at optimal levels. Heat sinks are used with high-power semiconductor devices such as power transistors where the heat dissipation ability of the component itself is insufficient to moderate its temperature.

A heat sink (Fig. 3.6) is designed to maximize its surface area in contact with the cooling medium surrounding its internal slots. (e.g. air or other cooling liquid like water). Thermal adhesive or thermal grease improve the heat sink's performance by filling air gaps between the heat sink and the heat spreader on the device. A heat sink is usually made of copper and/or aluminum (*9)*.

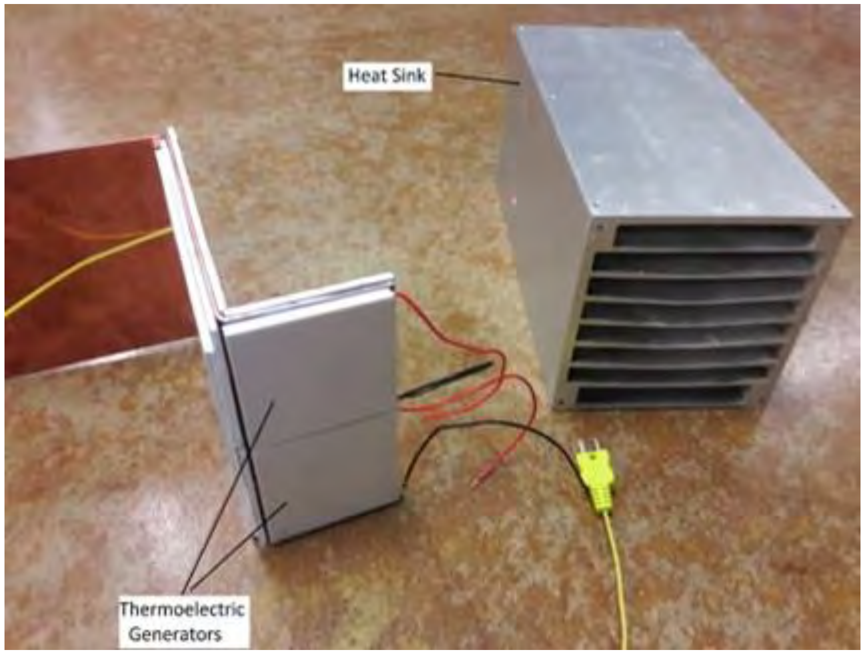


Figure 3.6: TEGs attached with heat transfer plate and Heat Sink

A heat sink with dimension of 30cm ×15cm×11.5cm was used. The heat sink was filled with sand or water which has high specific heat capacity.

In summary, the purpose of using heat sink is

- To absorb the released heat from the bottom surface of TEGs and transfer it to surrounding soil media.
- Maintain the temperature of bottom of TEGs to not exceed the surrounding soil medium.

3.4 Thermoelectric Generators

The TEGs are solid state devices used in power plants that convert temperature gradients directly into electric power. TEGs consist of three major components: thermoelectric materials, thermoelectric modules and thermoelectric systems that interface with the heat source.

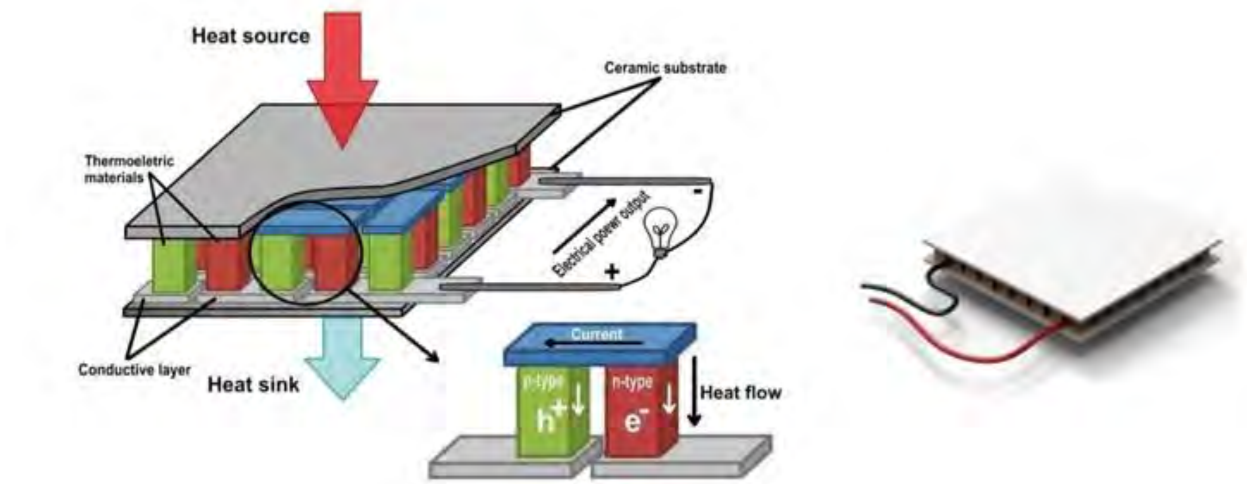


Figure 3.7 Schematic diagram of the internal components of TEG *(10)*

Figure 3.7 represents basic constituents of a TEG *(10)*. Thermoelectric materials generate power directly from heat by converting temperature gradient into electric voltage. These materials must have both high power factor (i.e., mWatts/ºC) and low thermal conductivity. Having low thermal conductivity ensures that no significant amounts of heat from the warm side of the TEG flows into the cooler side, thus reducing the temperature gradient driving thermoelectricity. Traditionally, the main three semiconductors known to have both low thermal conductivity and high power factor were bismuth telluride (Bi2Te3), lead telluride (PbTe), and silicon germanium (SiGe) (*11*). A thermoelectric module is a circuit containing thermoelectric materials that generate electricity from heat directly. A thermoelectric module consists of two dissimilar thermoelectric materials joined at their ends. There are two types, namely, n-type (negatively charged) and p-type (positively charged) semiconductors *(11)*. In this study two types of TEG were used; a) a 6.4cm×6.4cm TEG commercially named as TXL-287-03Z (*12*) and b) a 4cm x4cm TEG commercially named as SP18489*(13)*.

4. Safety Risk Assessment

In order to fully justify the functionality and compatibility of the prototypes with Safety Management Systems for Airport Operators, they were developed with compliance to the FAA Advisory Circular 150/5200-37 *(14)*. The prototypes will harvest energy being installed at 2 cm below the runway/taxiway pavement shoulder edge which will be completely invisible as well as far away from runway traffic with no interference with any airport operation. Most of the instruments will be buried under runway/taxiway side soil. The prototypes are completely green, having no environmental impact, as opposed to energy generated from burning fossil fuels, thus reducing the emission of harmful gasses and particulate matters into the environment. These systems can be built from lead-free components, not affecting the quality of water runoff or drainage. They do not have any impact on runway pavement characteristics and emit no green-house gases.

5. Description of Technical Aspects and Design

Finite element (FE) analysis was conducted to evaluate different prototype designs to maximize output power. The analysis was performed using the commercial ABAQUS (version 6.14-1) software. This analysis will include different prototype materials, components dimensions and number of TEGs required to maximize the system output. This chapter also presents the lab-scale prototype fabrication using the findings from the finite element analysis as well as the field testing, data collection and evaluation.

5.1 Finite Element Analysis

The aim of the FE analysis, conducted using ABAQUS, was to study the optimum design materials and dimensions of the thermoelectric prototype. In order to get the maximum possible temperature gradient and output power from the prototype, some key parameters were examined, i.e., effective materials for the harvester components, design depth of the TEG, dimensions of the heat transfer plate as well as number of TEG units to be used. The FE analysis involved the following assumptions:

1. The prototype was analyzed as one-dimensional heat transfer problem with steady state flow
2. For each iteration, the pavement surface and soil temperature used as boundary conditions were assumed constant,
3. The prototype was thermally insulated i.e. no heat loss occurred during heat conduction.
4. The effective yield period for heat harvesting was considered eight hours a day (i.e.,10:00 AM to 6:00 PM).

The temperature difference between pavement surface and soil at a design depth is considered as the input heat source to the prototype which is termed as available thermal gradient (ΔT_o) to the prototype. The temperature difference between heat transfer plate and top surface of heat sink i.e. temperature difference between the top and bottom surface of the Thermoelectric generator (TEGs) is considered as recovered thermal gradient by the prototype (ΔT) which is consumed by TEGs for electrical power generation.

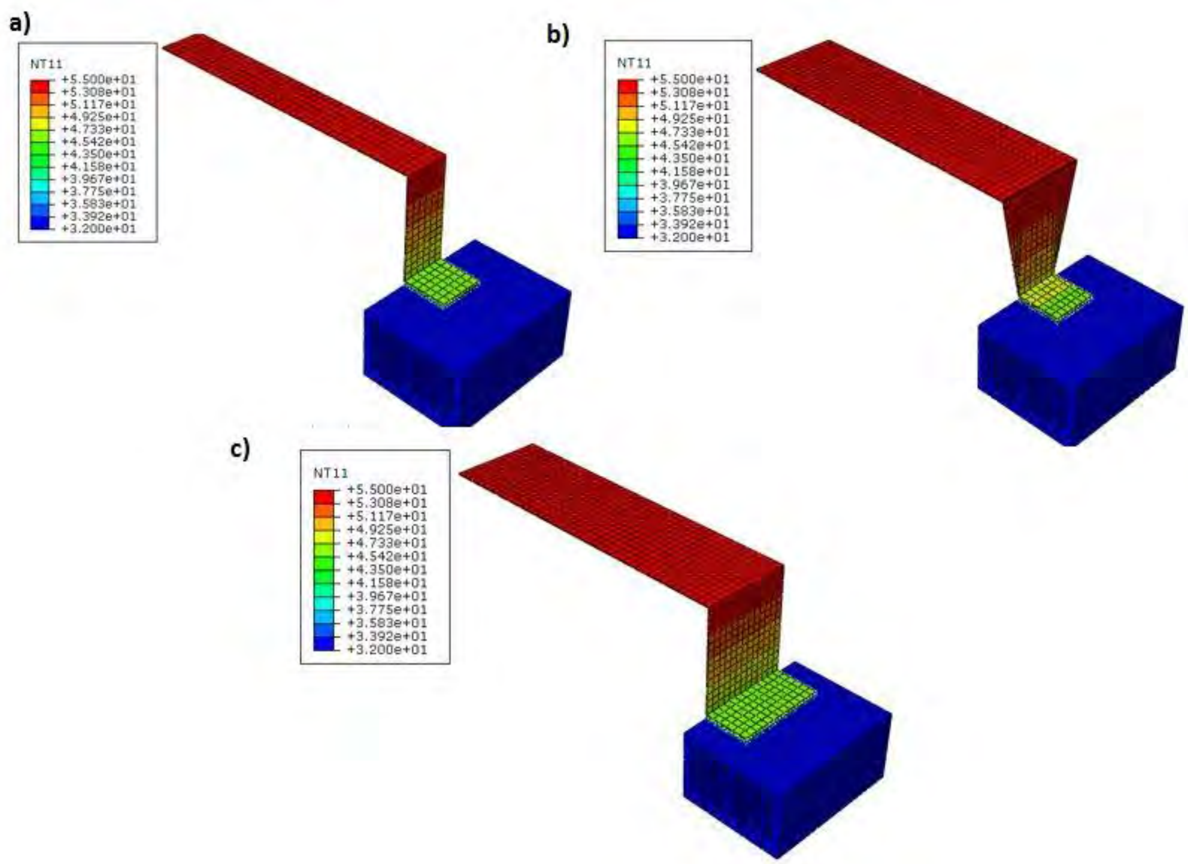


Figure 5.1: Finite element analysis on a) P_{L1} b) P_{L2} and c) P_{L3} Prototype

The FE model in Figure 5.1 consists of a Z-shape metal plate with thermal boundary conditions of 55°C at heat collector (representing pavement temperature) and 32°C at soil temperature under 18 cm of depth. A one-dimensional steady state flow analysis was conducted to determine the temperature at heat transfer plate and top surface of heat sink. The model was used to study the above mentioned key parameters to justify the optimum design elements for effective energy harvesting prototypes. The ultimate goal is to transfer that gradient between top and bottom surface of the TEG. With respect to the thermal properties used in the FE, the TEGs have thermal conductivity of 32 W/m.k *(15),* while copper plate and aluminum heat sink have thermal conductivity of 385 and 205 W/m.k *(16)*, respectively

Table 5.1: Prototypes with 6.4cm×6.4cm TEGs

Model No.	No. of TEGS	Proposed dimensions of the prototype (cm x cm)			Dimension of Heat sink (cm x cm x cm)
		Heat collector	Heat Conveyor	Heat transfer plate	
P_{L1}	1	45 ×6.4	15×6.4	6.4× 6.4	30×15×11
P_{L2}	1	45 × 12.5	15× (12.5+6.4)/2	6.4× 6.4	30×15×11
P_{L3}	2	45 × 12.5	15 × 12.5	6.4×12.5	30×15×11

Table 5.2: Output of FE analysis for prototype with 6.4cm x 6.4cm TEGs

Model No.	Boundary Conditions			Input to Thermo-Electric Generators		
	Road Surface Temperatures (^{0}C)	Soil Temp. under 180 mm depth (^{0}C)	Available Temp. Gradient (ΔT_o) (^{0}C)	Temp. on Heat Transfer Plate (^{0}C)	Temp. on heat sink (^{0}C)	Avg. Recoverable Temp. Gradient (ΔT) (^{0}C)
P_{L1}	55	32	23	45-47	34-35	11.5
P_{L2}	55	32	23	47-49	34-35	13.5
P_{L3}	55	32	23	45-47	34-35	11.5

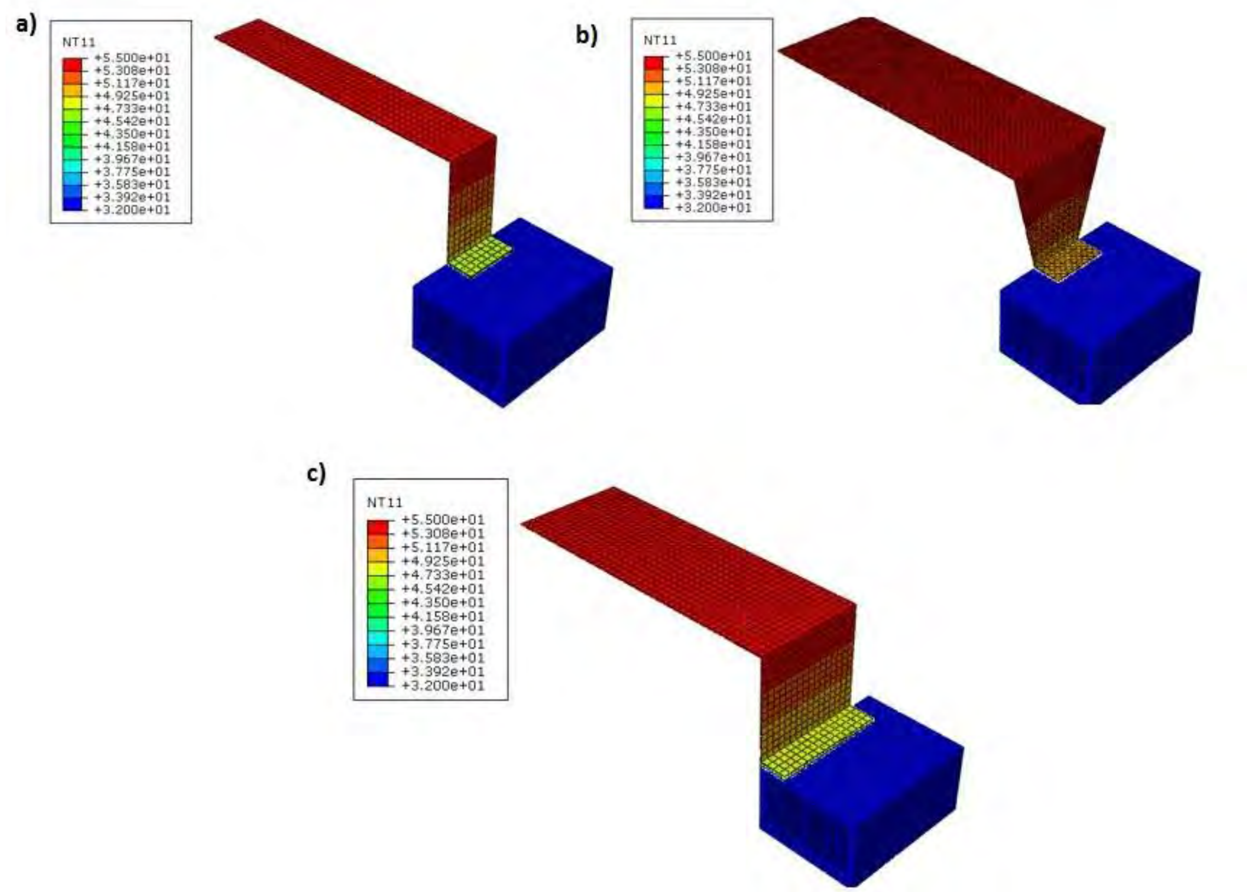


Figure 5.2: Finite element analysis on a) P_{S1} b) P_{S2} and c) P_{S3} Prototype

Table 5.3: Prototypes with 4cm×4cm TEGs

Model No.	No. of TEGS	Proposed dimensions of the prototype (cm x cm)			Dimension of Heat sink (cm x cm x cm)
		Heat collector	Heat Conveyor	Heat transfer plate	
P_{S1}	1	45 ×8	15×8	4× 8	30×15×11
P_{S2}	1	45 × 16	15× (16+8)/2	4× 8	30×15×11
P_{S3}	2	45 × 16	15 × 16	4×16	30×15×11

Table 5.4: Output of FE analysis for prototype with 4cm x 4cm TEGs

Model No.	Boundary Conditions			Input to Thermo-Electric Generators		
	Road Surface Temperatures (^{0}C)	Soil Temp. under 180 mm depth (^{0}C)	Available Temp. Gradient (ΔT_o) (^{0}C)	Temp. on Heat Transfer Plate (^{0}C)	Temp. on heat sink (^{0}C)	Avg. Recoverable Temp. Gradient (ΔT) (^{0}C)
P_{S1}	55	32	23	47-49	35-36	12.5
P_{S2}	55	32	23	49-51	36-37	13.5
P_{S3}	55	32	23	47-49	35-36	12.5

Although the P_{L2} represent higher thermal gradient, P_{L3} was selected over P_{L2} for lab testing and field evaluations. The reason is P_{L2} prototype model uses only one TEG (table 5.1) to transform energy whereas P_{L3} uses two TEGs even though P_{L3} prototype had 2^{o}C less thermal gradient (table 5.2), the output electric energy of P_{L3} was higher than P_{L2} due to using 2 TEGs. The second chosen prototype was P_{S3} **(**figure 6.2**)** with 4 TEGs (4cm× 4cm) whose dimensions are: Heat collector of 45cm × 16cm, Heat conveyor with dimensions of 15cm× 16cm and Heat Transfer Plate of 4cm×16cm (Table 5.3). The reason of selecting P_{S3} (table 5.4) is similar regarding selecting P_{L3}.

5.2 Prototype Fabrication

Multiple FE iterations of plate dimensions and number of TEG units were considered under same boundary conditions. Based on the FE result prototype PL3 and PS3 was fabricated for lab and field test (Figure 5.3).

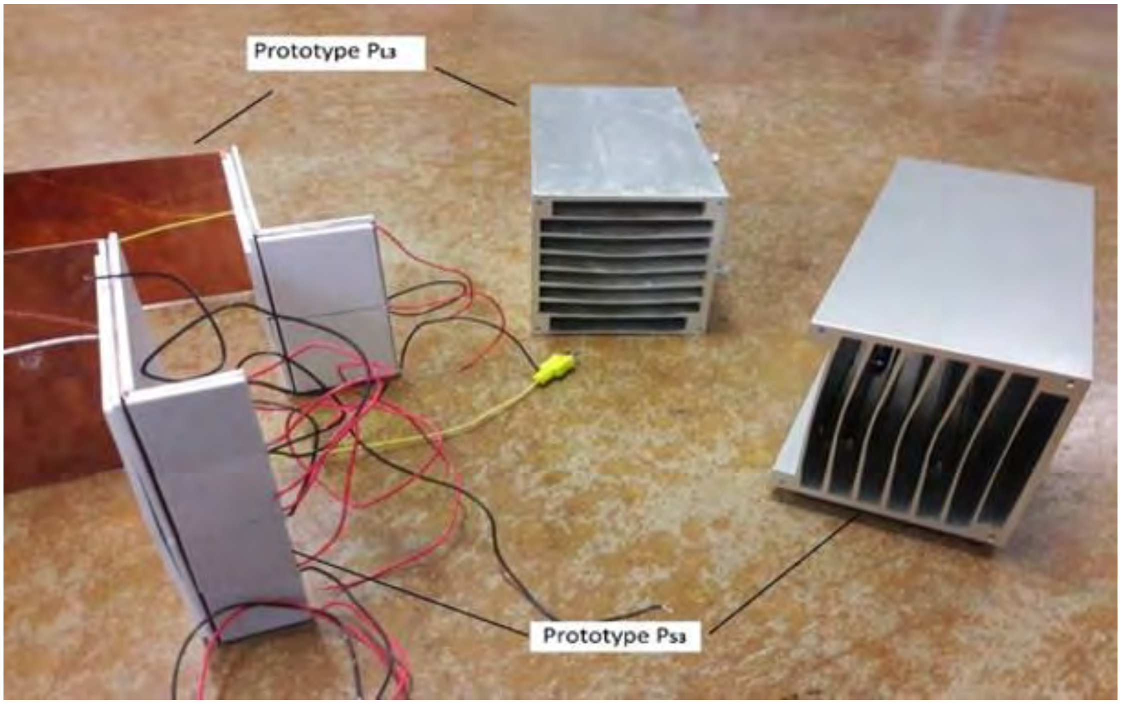


Figure 5.3: Prototype P_{L3} and Prototype P_{S3} fabrication for lab experiment

5.3 Lab Experiment Setup

Once the prototypes are fabricated, the lab experimental setup (Fig.5.4) became much simpler. For lab test the following equipment are needed:

1. Energy Harvesting Prototype (P_{L3} or P_{S3})
2. Hot water tub
3. Flat plate type Electric Heater
4. Metallic water tub
5. K-type 4 channel thermometer data logger with probes
6. Metrahit Power Meter

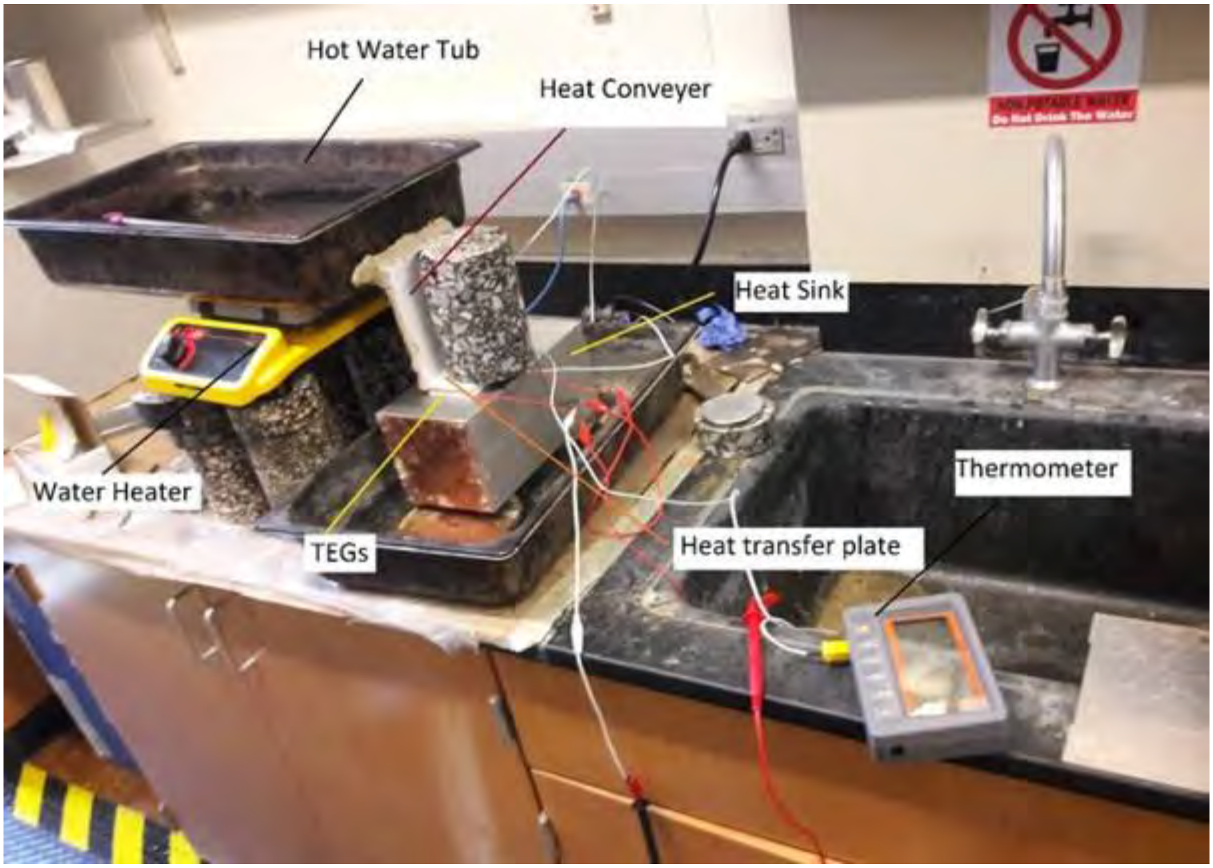


Figure 5.4: Lab experimental setup

In lab experiment the heat collector of the prototype is inserted into the hot water tub through a thin opening at the bottom of it (Fig. 5.4). This water tub is placed on a flat hot plate with a digital temperature regulator. The heated water is simulated as pavement surface which functions as a heat source to the prototype. The soil temperature is simulated with the ambient room temperature (23^{o}C) during the experiment. The TEGs are sandwiched between bottom of heat transfer plate and top surface of the heat sink. The heat sink is usually filled with liquid of high specific heat capacity like water. Before starting the test, the heat sensor probes of the K-type 4 channel thermometer data logger was attached to hot water in the tub which simulates the road surface temperature (T_1), Heat transfer plate temperature is referred to as T_2, heat sink surface temperature is referred to as T_3 at the bottom of TEGs, room temperature, T_4 which simulates soil temperature at design depth. The conducting plate was fully inserted into the heated water tub.

The first sensor probe was immersed in the hot water to collect the temperature data T_1, the second probe was fixed with glue on the top surface of heat transfer plate before isolating the top surface of heat transfer plate by PVC sheet which ultimately collect the temperature T_2. Third probe was fixed in between TEGs and heat sink with thermal paste mix to record temperature T_3. The fourth probe was kept in open air to measure the room temperature. The TEGs are connected in series and the output voltage, current and power were measured by a power meter.

5.3.1 Laboratory Testing Conducted on Prototypes

Laboratory experiment on the prototypes was conducted in two steps. In first step thermal data was collected to generate the output temperature gradient curve with time and in the second step electric current and voltage data was collected to generate the output power curve with time.

Before running the test, the temperature sensor probes are attached to four different collecting points. To ensure the accuracy of the data collection, a sensor probe was glued on the upper surface of the heat transfer plate. The other three are clamped on heat sink top surface, hot water tub, and outside heat sink accordingly. Tests were run at three different water tub temperatures of 45^{o}C, 50^{o}C and 55^{o}C while the heat sink surrounding (representing soil) temperature ranges from 26^{o}C and 28^{o}C. Using the data logger, the temperature was collected over a period of 40 to 50 min at four spots in the prototype P_{L3} (Fig. 5.5); water tub, heat transfer plate at top of TEG, heat sink at bottom of TEG and room temperature.

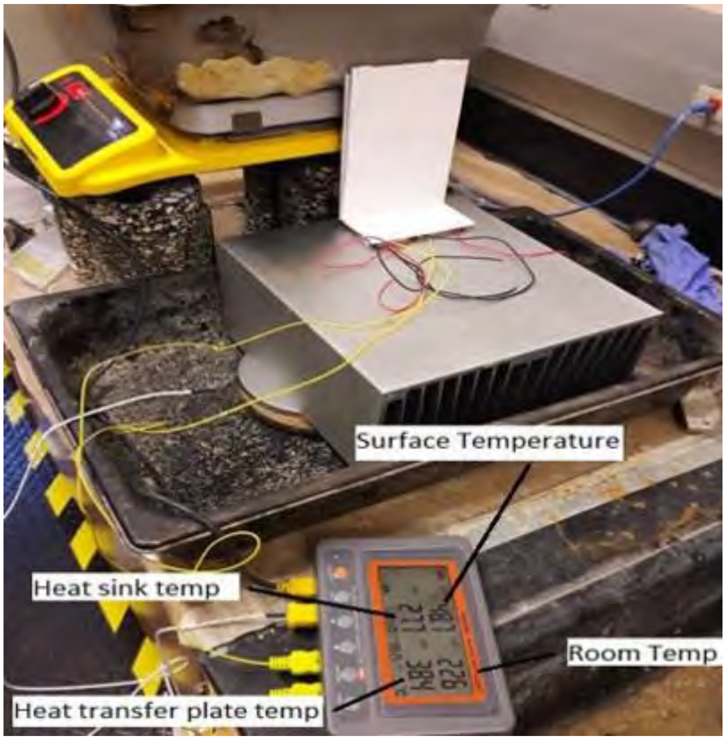


Figure 5.5: Temperature data

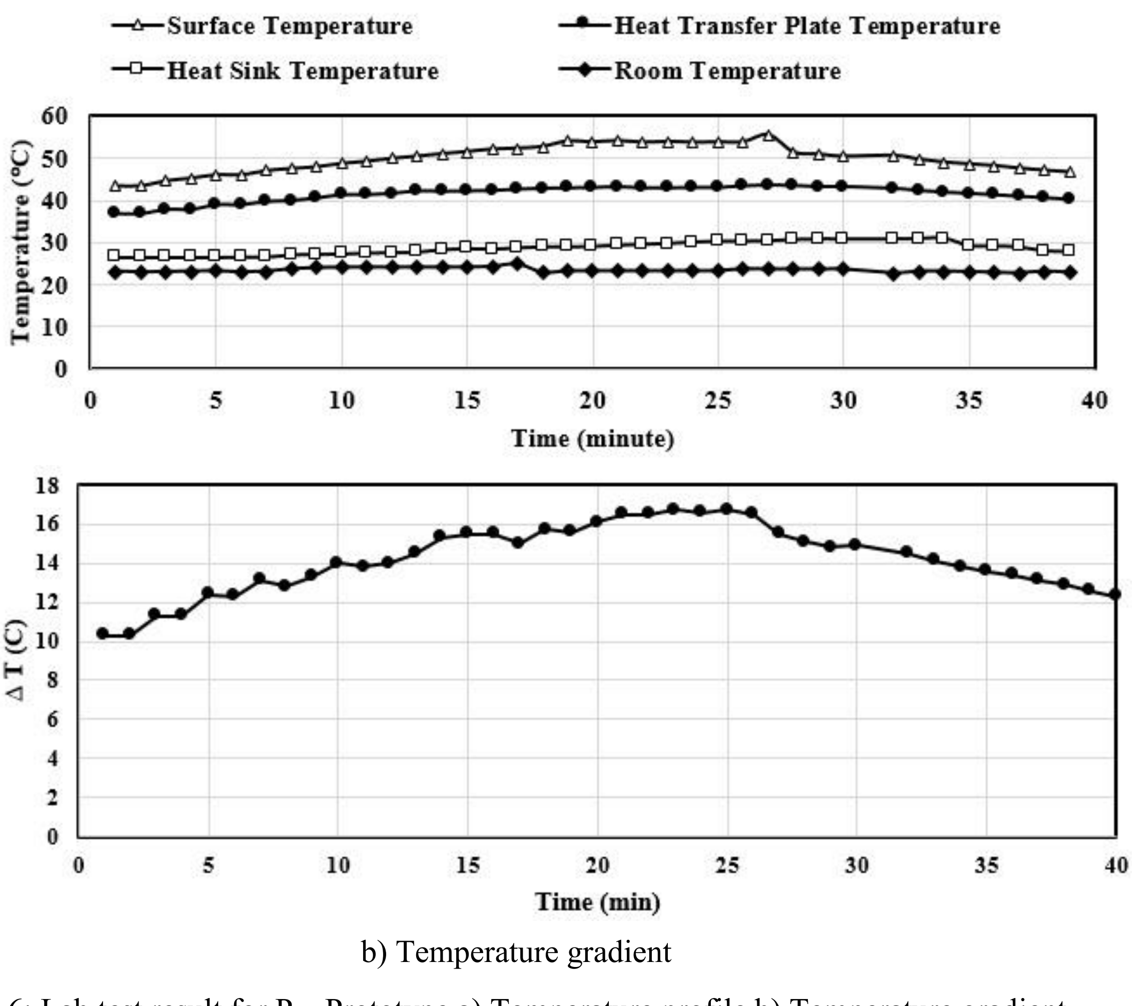
Several tests were conducted on prototype P_{L3} for different boundary conditions. The average length of data collection was 40 to 50 minutes. During the tests the heat sink was filled with water. Results showed that the imposed temperature gradient was in the range of 21 to 26^{o}C and the output temperature gradient from the lab test was measured to be between 11^{o}C and 14^{o}C for prototype P_{L3} (Table 5.5).

Table 5.5: Testing results of output thermal gradient under different temperature inputs

Temperature Boundary Conditions			Input to Thermo-Electric Generators		
Hot tub/ simulated road Surface temperatures(^{0}C)	Room/simulated soil temperature under 15cm depth (^{0}C)	Available Temperature Gradient (ΔTo) (^{0}C)	Heat Transfer Plate temperature (^{0}C)	Heat sink top Temperature (^{0}C)	Recoverable Temperature Gradient (ΔT) (^{0}C)
45	21	24	36-39	27-28	11
50	24	26	40-43	28-29	12
55	26	29	43-45	29-30	14

Figure 5.6a showed temperature profile and output temperature gradient over time for prototype P_{L3}. There is a gradual increase in temperature observed from 5 to 15 minutes. Then the prototype reached its steady state. After 30 minutes as the imposed surface temperature gradually drops, the prototype components (heat transfer plate and sink) appear to follow the decrease in temperature. Figure 6.4b showed the output thermal gradient from the prototype PL3. There is a gradual increase in thermal gradient from 5 to approximately 15 minutes. Then the prototype gives steady thermal (Figure 5.6b) gradient up to 27 minutes. After 30 minutes a gradual decrease is observed.

a) Temperature profile



b) Temperature gradient

Figure 5.6: Lab test result for P_{L3} Prototype a) Temperature profile b) Temperature gradient

5.3.2 Electrical Data Analysis from Lab Experiment

Output voltage, current and power data was collected with Metrahit Power Meter (Figure 6.7). For both P_{L3} and P_{S3} prototypes. Also, an 8Ω resistor was attached with the TEGs to maximize the power output. The data was also recorded for 40 to 50 minutes.

Figure 5.7: Output voltage and current for P_{L3} prototype

For prototype P_{L3}, the output voltage was in the range of 350mV to 520mV where for the prototype PS3 the output voltage was in the range of 250 mV to 400mV (Fig. 5.8).

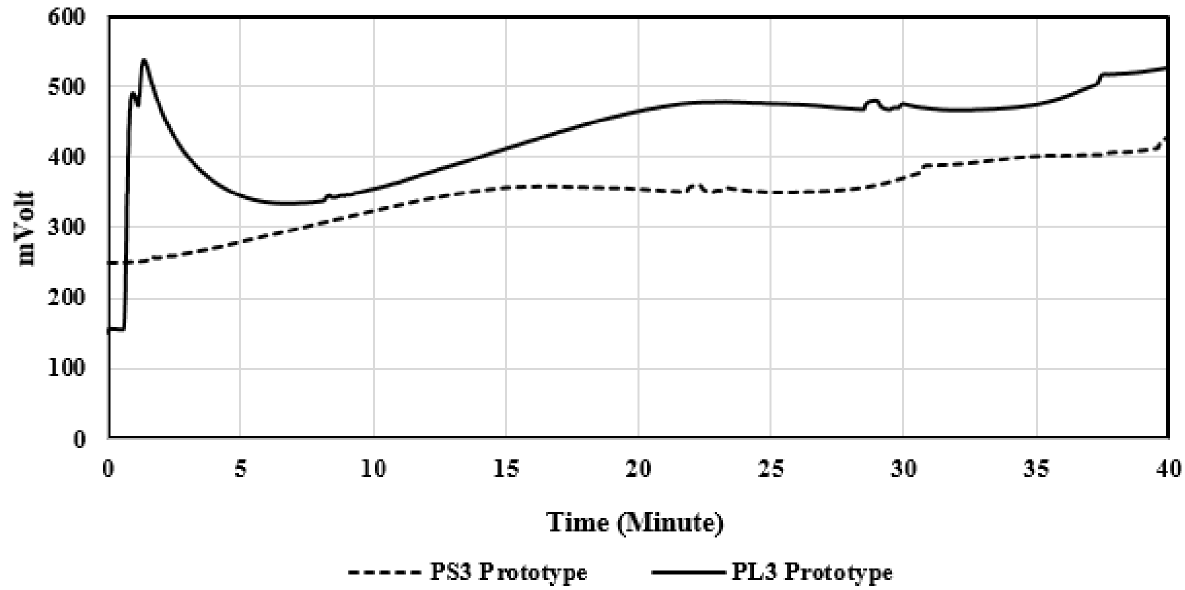


Figure 6.8: Lab result of output voltage with time for P_{S3} and P_{L3} Prototype

For prototype P_{L3}, the output current was in the range of 30mA to 45mA where for the prototype PS3 the output current was in the range of 25 mA to 35mA (Fig. 5.9).

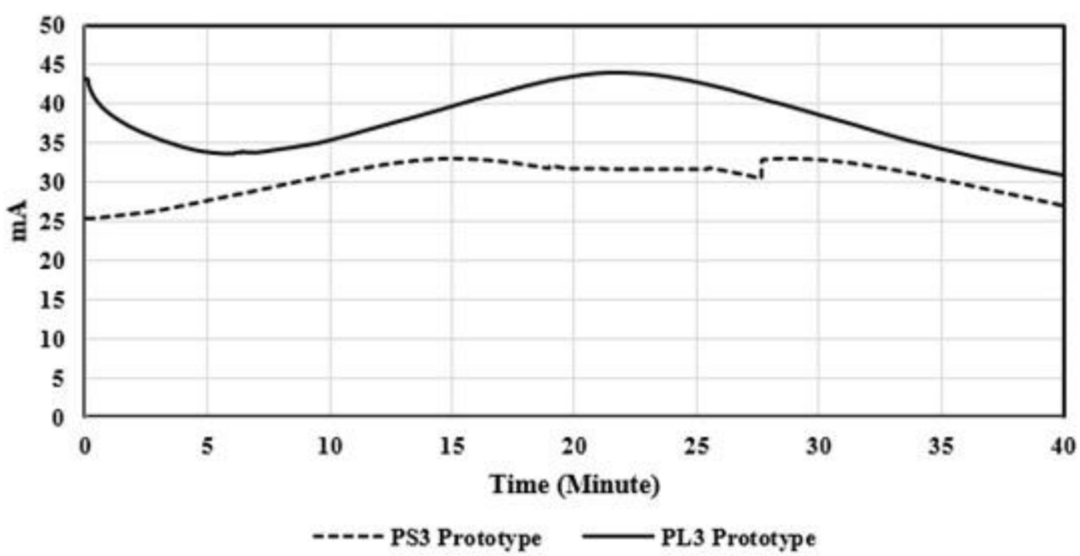


Figure 5.9: Lab result of output current with time for P_{S3} and P_{L3} Prototype

For prototype P_{L3}, the output power was in the range of 15mW to 22mWwhere for the prototype P_{S3} the output power was in the range of 7mW to 13mW (Fig. 5.10).

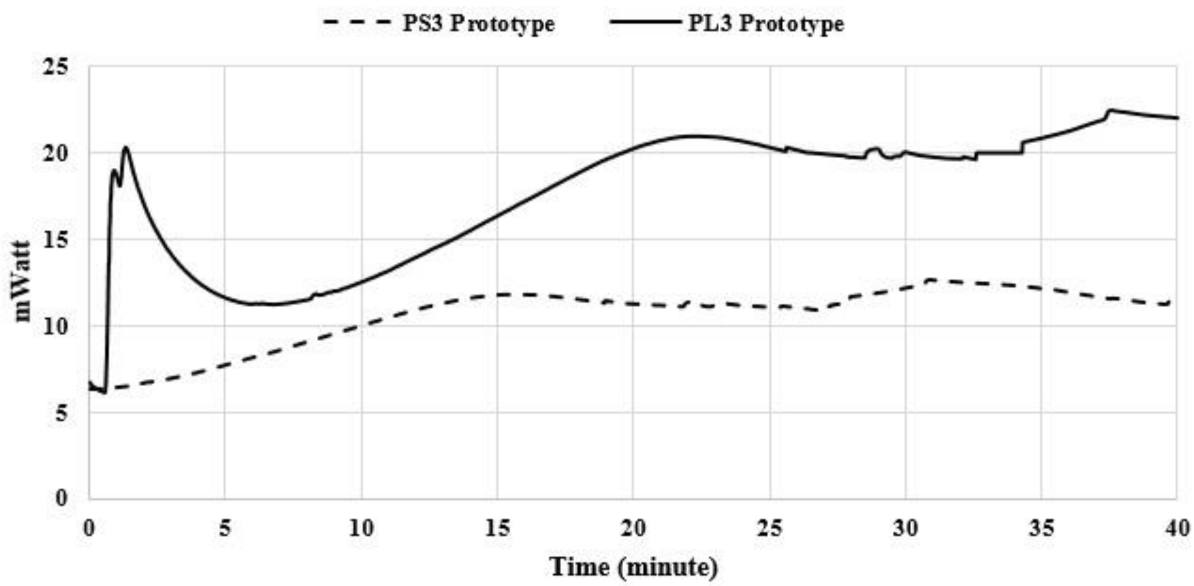


Figure 5.10: Lab result of output power with time for P_{L3} and P_{S3} Prototype

Hence, the resulting output power was in the range of 7 mW to 22 mW. In summary the potential average rate of power generation for this thermoelectric energy harvesting prototype is 1.2mW/^{o}C (i.e, an average output of 14 mW for ΔT of 12^{o}C).

5.4 Field Evaluation and Data Collection

In this chapter an evaluation of the prototype functionality in the field is examined. As it was not possible to install the prototype for field evaluation as well as data collection in a functional runway pavement, a similar pavement section was selected in the main campus of the University of Texas at San Antonio as a substitution to runway/taxiway pavement. The energy harvesting prototypes were inserted in the pavement for field testing and monitoring their performance.

5.4.1 Site Selection

Analyzing the pavement layer dimensions of a typical runway/taxiway, a similar pavement segment in the west campus of the University of Texas at San Antonio campus's roadway was selected to evaluate the prototype. The site was identified to minimum exposure to traffic and sun light obstruction on pavement surface. It was also necessary to allocate a pavement surface without concrete curb or side walk for easy access to roadside soil materials. As shown in Figure 5.11, the site was closed to one of the civil engineering laboratories.

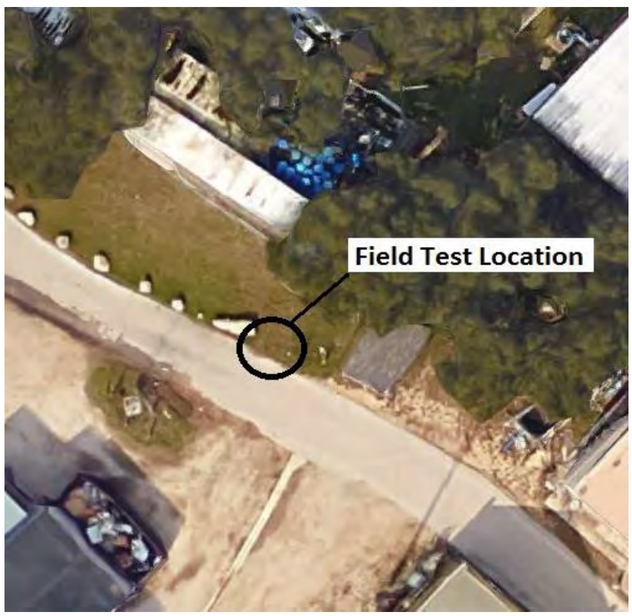


Figure 5.11: Suggested locations for field test as a substitution to runway/taxiway

5.4.2 Site Preparation and Construction

The two identified prototypes (PL3 and Ps3) were chosen for installation side by side. After site selection arrangements were made for construction work to install the prototypes into the pavement to road side soil (Fig. 5.12). The prototypes were kept 30 cm apart from each other during installation.

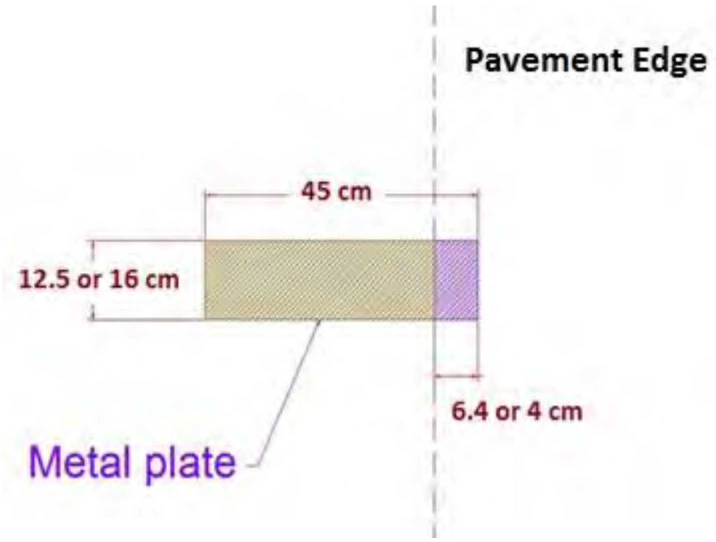


Figure 5.12: Plan or top view of the prototype

Two strips of asphalt concrete surface with dimensions of 50cm x 18cm and depth of 4 cm was taken out of the pavement edge as shown in Figure 5.13a. The strips were cut at 30 cm apart from each other to allow for installation of two prototypes. In the soil side adjacent to the shoulder a pit of 100cm x 50cm x45 cm was dug for installation of heat sink and heat conducting plate. At the bottom of the pit the heat sinks were placed such that its top surface is 18 cm below the road surface. A 5cm×5cm wood block and flat metal sheets were used to provide a support to the heat sinks. For the prototype PL3, the heat sink was filled with water and supported by a flat metal sheet. For prototype PS3, the heat sink was partially filled with sand and supported by a wood block.

The TEGs were glued with a thermal paste at the bottom of the heat transfer plate before bringing them to the test site. The heat conducting metal plates were placed and leveled in the two strips as shown in Fig. 5.13b. The bottom surface of the TEGs were then glued with the top surface of heat sink using thermal paste. Four K-type temperature sensor probes were fixed with the system to collect the temperature data. First probe was attached with thermal paste mix on top surface heat collecting plate before placing the asphalt mix on the top of it. The second probe was glued on the top surface of heat transfer plate before isolating the top surface of heat transfer plate by PVC sheet. A third probe was fixed in between TEGs and heat sink with thermal paste mix. The fourth probe sensor was place in to the soil at the same level of heat sink.

Figure 5.13 : a) Pavement and soil cut b) Installing prototypes c) Covering with fresh HMA d) After field installation

Then top surface of the heat conducting metal plate were covered with hot mix asphalt at to restore the road surface (Fig. 5.13c). Temperature sensor probe's wire including the TEGs wires were taken out to the soil surface before the pit is backfilled to the existing ground level (Fig 5.13

d). The excavated soil was used for the back-filling after installation was complete. Also other filling materials with lower thermal conductivity and heat capacity can be used as backfilling.

5.4.3 Data Collection and Analysis

A four channel temperature data logger (AZ Instruments 4 Channel K Type Thermometer SD Card Data Logger) was used to collect the temperature data. A power meter (Gossen METRAHIT) was used to measure output voltage, current and power. The TEGs were connected in series and their positive and negative poles are extended with connecting wires up to the ground surface. The output voltage *V* and current *I* is measured with external resistance of 8.3Ω.

Pavement Surface Temperature, T_1 = 50.1 ^{0}C
Heat Transfer Plate Temperature, T_2 = 38.9 ^{0}C
Heat Sink Top Temperature T_3 = 32.9 ^{0}C
Soil Temperature under 18cm T_4 = 32.4 ^{0}C

Available thermal gradient $\Delta T_o = T_1 - T_4$ = 17.7 ºC

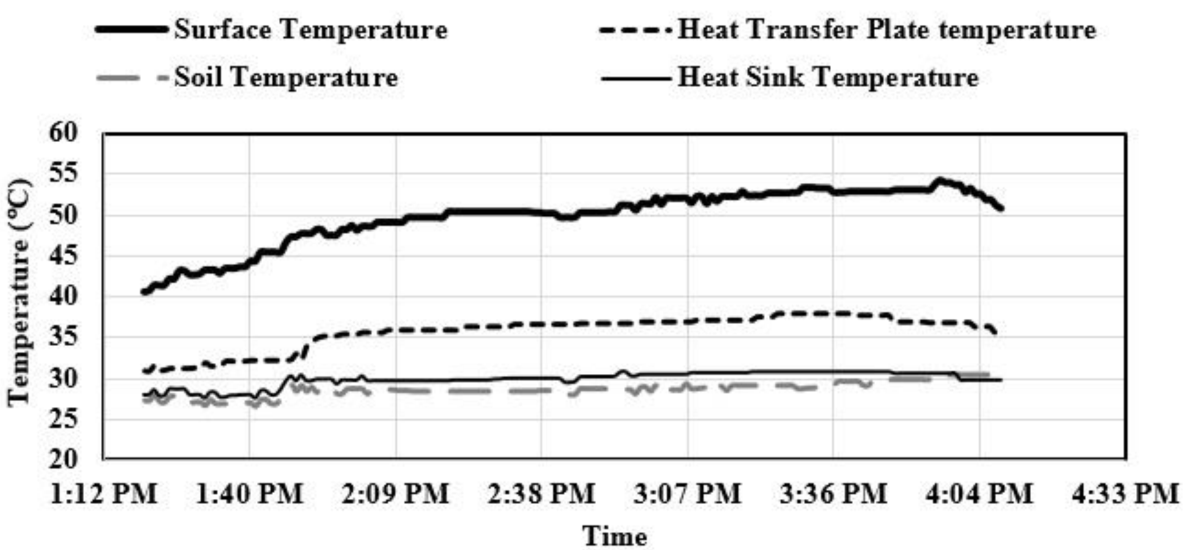
Recovered thermal gradient by Prototype P_{L3} for power generation $\Delta T = T_2 - T_3$ = 6 ºC

Figure 5.14: Sample field temperature data for Prototype PL3

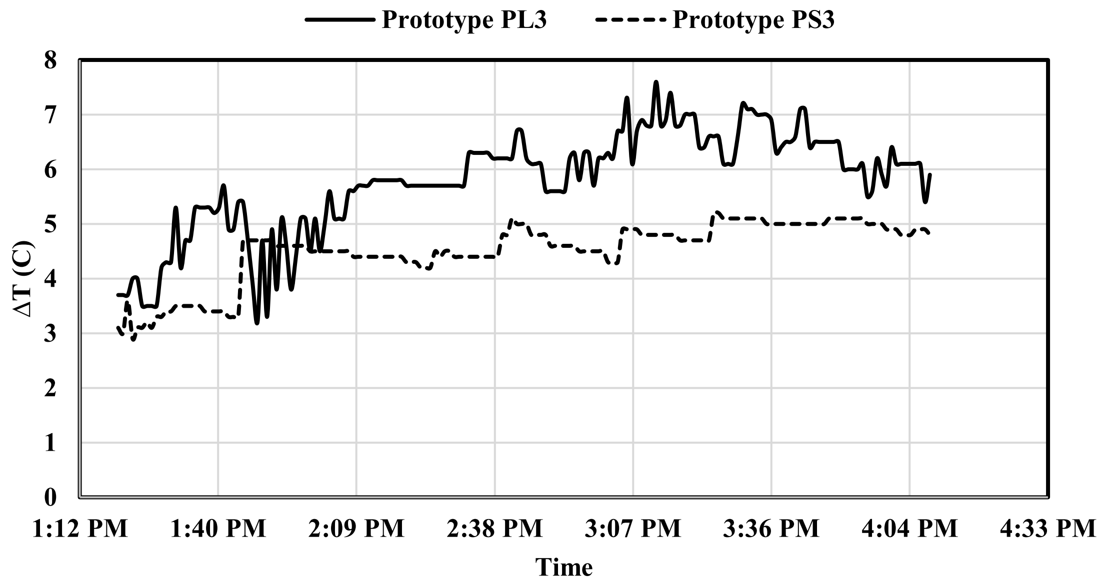
Output Voltage = **0.6486 V**
Output Current= **22.03 mA**
Output Power = **14.28 mW**

Figure 5.15: Sample field data collection on prototype P_{L3}

The data was collected during the daytime between 10:00 AM and 6:00 PM for both prototypes (Fig. 5.14 and 5.15). The average thermal output gradient observed from prototype P_{L3} and PS3 are in the range of 5°C to 7.5°C (Fig. 5.17).



a) Temperature profile



b) Temperature gradient for Prototype P_{S3} and P_{L3}

Figure 5.17: Field results during day time showing a) temperature profile and b) gradient for Prototype P_{L3} and PS3

For prototype P_{L3}, the output power was in the range of 8 mW to 14 mW and for the prototype PS3 the output power was in the range of 7 to 9.5mW (Fig. 5.18).

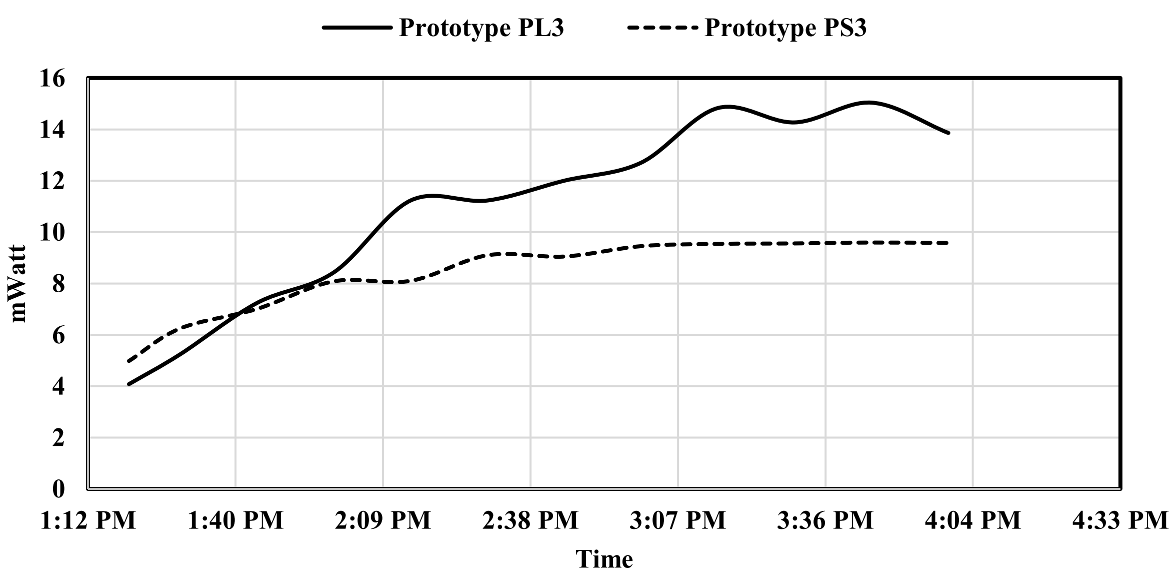


Figure 5.18: Field results during day time showing output power of Prototype P_{L3} and P_{S3}

5.5 Sensing Design Capability

The sensing case includes a load sensors, a conversion module, storage capacitors, an analogue to digital (AC/DC) converter, memory for data storage and a sealed enclosure (Figure 5.19). The enclosure is installed under the energy harvesting prototype to collect; type (number of axles) and weight-class of the plane, speed at a given point, pavement stresses, pavement temperature and moisture, etc.

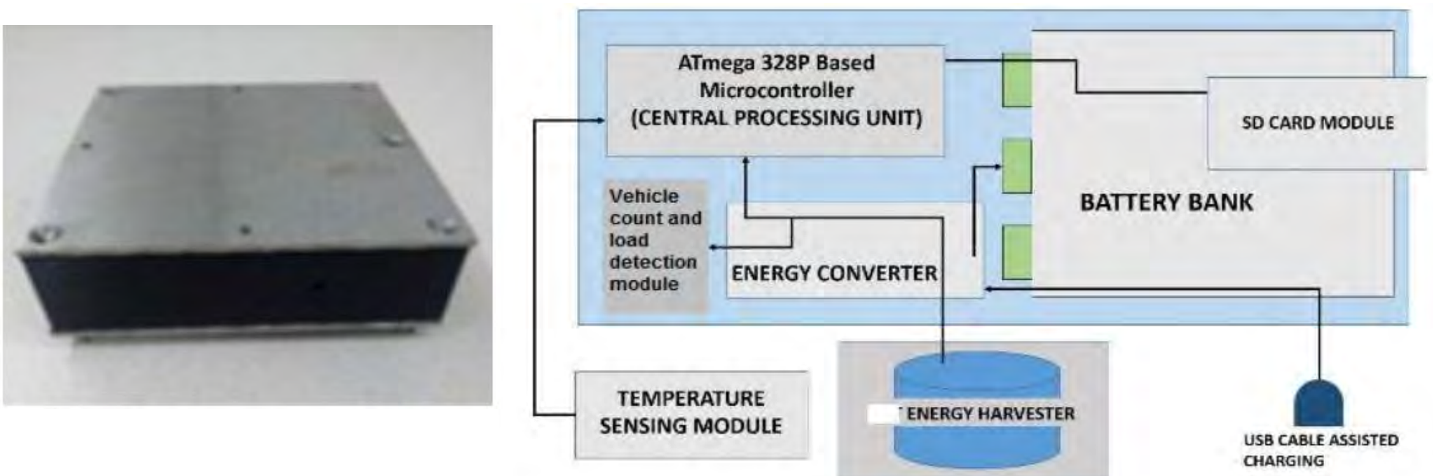


Figure 5.19. a) Sensing enclosure to seal sensors and electronic components b) Block diagram of micro-power sensing and data logging module

5.6 Cost of Prototype

For the prototype P_{L3} the cost of the heat conducting metal plate was 35.0$, two thermoelectric module costs 110.0$ (55.0$ each), heat sink costs 35.0$, thermal isolation costs 10.0$. Hence excluding sensing devices and labor costs, the total costs of the system was 190.0$. For the prototype P_{S3} the cost of the harvester was 35.0$, four thermoelectric module costs 14$ (3.5$ each), heat sink costs 35.0$, thermal isolation costs 10.0$. Hence excluding sensing devices labor costs, the total costs of the system was 94.0$.

For the PL3 and PS3 prototypes the cost of the materials excluding installation are $190 and $94, respectively. Based on the experimental data collected and the FE analysis, PL3 prototype with heat transfer area of 6.35cm×12.7cm strip can generate an average of 12 mWatt. The recoverable power density per square feet of pavement is 113.33 mWatt (approximately) and the daily energy accumulation of the prototype may yield up to 1.0 Wh considering 8 hour of operation per day.

6. Interactions with Airport Operators and Industry Experts

To design an energy harvesting prototype for airport runway pavement we needed a typical runway pavement structural and layer information including layer dimensions, material specifications. To determine the input thermal gradient to our prototype we had to predict the pavement temperature profile first. To do so we needed mean hourly weather data for a year of the airport including temperature, air speed, solar radiation. To get these data, we contacted airport official. We contacted Mr. Loyce D. Clark, Chief Asset & Planning Officer of Aviation Department at San Antonio International Airport for runaway pavement structural and layer information. We also contacted Mr. Navneet Garg, PhD, Project Manager, ANG-E262 of Federal Aviation Authority for weather data of the airport as well as for structural information of typical runway pavement. Based on the airport data we did finite element modelling as well as designed our prototype for laboratory and field test. We also contacted Mr. Paul Krueger, Instrument Mechanic, Mechanical Engineering & Biomechanics Machine Shop, University of Texas at San Antonio(UTSA). Mr. Kruger helped a lot during building our prototypes. For the field installation of our prototype, we also needed help of Mr. Mike Nichole of UTSA facilities department. For instrumentation and other electronic devices, we contacted TXL Group, 2000 Wyoming Ave, El Paso, TX 79903 and TEGMART, 44 Hull Street Randolph VT 05060.

7. Projected Impact

Thermal harvesting prototypes using the temperature gradients within asphalt pavements of runway and taxiways appear to have the potential for sustainably generating energy. The energy harvesting process is green and environmental friendly as well as inexpensive. It is not obtrusive and it does not interfere with the traffic. Furthermore, if the conductive plate top is installed 2 cm below the asphalt concrete pavement surface, the harvester would not interfere with periodic pavement overlay activities.

Two prototypes of thermal energy harvesters were developed. Numerical analysis using FE was used to quantify the components design. Laboratory and field testing was conducted to validate the functionality of the prototypes. Under the conditions tested, a strip of average 5-inch length along traffic directions can generate an average of 12 mW of electric power continuously over a period of 8 hours a day. The recoverable power density per square feet pavement section is 113 mW (approximately) and the daily energy accumulation of the prototype is 1Wh.

The produced power may look very small for conventional electronic devices. But it can be used for powering pavement health monitoring devices like strain gauge, pressure sensors etc. which consumes power as low as 3mW *(17)* and communication devices especially in off-grid areas where it will cost millions of dollars to power these devices from on-grid electricity. Also, it can be an alternate source of self-powered electronic signs or markings in runway and illumination with LEDs in remote runways in off grid areas. A P_{L3} prototype Can power a bunch of 10 number of LEDs (each with 1mW) (*18*) for eight hours. With the help of proper electronic devices, the output power can be stored by charging capacitor or batteries for continuous supply of electricity.

Appendix A: Contact Information for All Advisors and Team Members

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Appendix B: Description of University

The University of Texas at San Antonio (UTSA) is a state research university in San Antonio, Texas, United States. With over 28,000 students, it is the largest university in San Antonio and the eighth-largest (2014) in the state of Texas *(19).* Its three campuses span over 747 acres of land, with its main campus being the largest in the University of Texas System. UTSA offers a wide array of academic studies, with 133 undergraduates, 51 graduate and 24 doctoral programs. In 2012 and 2013, it was selected by Times Higher Education as one of the best universities in the world under 50 years old.

UTSA is a member of the Oak Ridge Associated Universities, a consortium of the nation's major doctorate-level universities dedicated to collaboration and scientific advancement. It is an institutional member of the Hispanic Association of Colleges and Universities, recognizing its influence and role as a Hispanic-serving institution. UTSA is also a member of the American Association of State Colleges and Universities, an organization of public institutions that seek to both offer educational excellence and opportunities to historically under-served populations.

Established in 1969, UTSA has evolved to become the fourth largest institution within the UT System *(20).* Through an aggressive expansion of its academic funding, the university devoted over $56 million to research in 2011. Its football team has competed in Conference USA since 2013, previously playing a stint in the WAC and as an FCS independent.

Alongside seven other emerging research institutions, The University of Texas at San Antonio is currently in competition to become Texas' third flagship university.

Appendix C: Description of Non-University Partners

All partners involved with this project are affiliated with the University of Texas at San Antonio.

Appendix E: Evaluation of Educational Experience Provided by the Project

Students

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?

Designing an energy harvesting system from runway pavement infrastructure is a novel concept that has not been fully explored yet. The prototype we designed for participating in ACRP was the key part of my master's thesis. The concept and the technology was new to us and we had the opportunity to explore a technology that was completely uncovered. So ACRP University Design Competition for Addressing Airports Needs surely provided us a meaningful learning experience.

2. What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?

Developing an energy harvesting systems from temperature gradients within a runway pavement is completely an unexplored research area. Very Limited literature describes efforts to develop such systems. Hence it was very big challenge for us to develop a new methodology as well as prototypes that yield maximum power output from the input temperature gradient. To overcome this, we had to work on several models and had to run multiple number of simulations using ABAQUS (Finite Element software) considering all the factors and constraints. Finally, we could design prototypes that produces optimum power output during lab experiment as well as field test.

3. Describe the process you or your team used for developing your hypothesis.

Before developing an energy harvesting prototype, we had to examine whether there is adequate thermal gradient available to run the system throughout the country. To establish this fact, we had to collect weather data (mean hourly temperature, wind speed, solar radiation) from 17 different states that sporadically represents whole United States and we run finite element analysis using TEMPS software to predict temperature profile of runway pavement along with depth. The output result from this analysis established our desired hypothesis for developing a prototype to harvest energy.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Participation by industry in the project was quite appropriate, meaningful and useful. The industry expert provided us with the input data to design the prototype as well as run the simulation. Without their cordial cooperation, it would not be easy for us to get the success in modelling the appropriate methodology to design the energy harvesting system.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

Working in a completely new research area and developing a new technology provided us a wide range of new learnings and facilitates the new way towards innovations. This research helped us to analyze a problem/issue. Also provided us important learning on studying literature behind this issue effectively, technical design of procedures to overcome the problem/issue.

Faculty

l. Describe the value of the educational experience for your student(s) participating in this competition submission.

The student had the opportunity to work on a new research area which is harvesting energy from the runway pavement which helped him to enhance his substantial understanding not only in Civil Engineering but also in Mechanical as well as Electrical Engineering. Also, the analytical skill and technical report writing skill the student gained will be a great addition to his future career.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

Yes. The learning experience the student gained from this research work completely appropriate to the course level.

3. What challenges did the students face and overcome?

Ans. The challenges the student face is that he worked on a research area that had very limited literature and he had to develop a methodology that harvest energy from runway pavement most efficiently. However, through several simulation and lab experiment and field test he justified his model’s functionality.

4. Would you use this competition as an educational vehicle in the future? Why or why not?

Yes, I would surely use this competition as an educational vehicle in the future. Because this competition is a great source of motivation to the students towards innovation of new research arena.

5. Are there changes to the competition that you would suggest for future years?

This competition is excellent door way to new research and innovation for the airport infrastructural development. I would strongly support this program and encourage my future student to participate in this.

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