2014-2015 ACRP UNIVERSITY DESIGN COMPETITION

PECS - Design of a Self-Sustaining, Affordable Energy Generating System for Airports

Design Challenge: Airport Environmental Interactions

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Executive Summary

This report presents a solution to Technical Design Challenge 3, Airport Environmental Interactions, for the 2014-2015 Airport Cooperative Research Program University Design Competition. As stated in Challenge 3, airport operations must be carried out with consideration for how the environment could be adversely affected. This includes energy supply and efficiency.

To address the Challenge 3 directive, the Airport Consulting Team (ACT) has conceptualized, designed, and successfully prototyped the Piezoelectric Carpet System, or PECS. This system uses the energy output of a human step to illuminate LED lights integrated into PECS on a jet bridge. PECS is affordable compared to existing flooring-lighting systems with an approximate cost of $20/SF. The power output of PECS is 8,869.5 kWh per year, with an annual airport energy savings of $3,036.00 per year per jet bridge installation. The motivation for designing this system results from the need to design a completely new technology that has a positive impact on both the environment and airport operating costs. Three primary goals were considered in developing this system; 1- manufacturability; 2- commercialization; and 3- innovation. Ultimately, this system has been designed for implementation into any type of airport on a large or small scale for the purpose of reducing energy costs and consumption at the airport.

PECS has been successfully prototyped and tested in realistic conditions. The system has generated interest from a number of airports, with multiple airport experts expressing a desire to follow the development of PECS.

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1- Problem Statement

The Airport Cooperative Research Program (ACRP) University Design Competition, funded by the Federal Aviation Administration (FAA), supports the innovative application of research and new technologies as they apply to airport operations and environmental interactions. In response to the charge of the competition, the Airport Consulting Team (ACT) has researched and designed an innovative and sustainable solution to growing airport energy needs through the use of piezo-technology. This technology converts mechanical energy into electrical energy that can be stored and used for lighting, sound and data collection. ACT has designed a fully functional and successful prototype that demonstrates a piezo-technology application that addresses high levels of energy consumption in airport operations. The piezoelectric carpet system, or PECS, is presented as a scaled design specifically applied to jet bridge flooring material. An example of a typical jet bridge is presented in Figure 1[1]. However airport applications are numerous for a full-scale implementation based on the PECS technology. The ultimate goal of the project was to design a commercially viable system that has the potential for use in high traffic airport settings.

Figure 1: Example of a general jet bridge walkway.

PECS delivers a cost-effective solution that contributes to reducing the high energy costs associated with running large airports, while providing an innovative, cutting edge energy capture system. Placed in high traffic airport areas such as a jet bridge walkway, (the structure connecting the gate to the plane), PECS functions through the action of footsteps. By simply walking across a section of PECS, the system produces and stores energy that is then used to power various low energy applications such as LED strips of lights integrated into the sections of the system. The prototype version of PECS consists of twelve 3” x 3” energy collecting cells, that, when depressed, activate piezoelectric elements that generate a charge. This charge then flows to a storage device, where it awaits distribution as energy. The system is completely self-contained and requires no external power source.

ACT’s ultimate goal was to produce a cost-effective, energy generating system that replaces traditional carpeted or tiled walkways in high traffic airport areas. As operational costs escalate, there is a need to actively investigate alternative sources of energy for airport operations that will ultimately offset energy costs. PECS, when fully implemented, addresses this issue.

2- Background

2.1- What is the Piezoelectric Effect?

Several materials, including quartz, topaz, and even bone, have the unique ability to generate an electric charge in response to mechanical deformation, called the piezoelectric effect. This phenomenon is reversible, meaning that not only will a deformation produce an electric charge, but the application of an electric charge to the material will cause a physical deformation. The charge generation results from a physical shifting of charge centers in the material when placed under stress. This movement generates an external electrical field. The attachment of a positive and negative lead to the material then allows for the collection of this charge. An illustration of this effect is shown in Figure 2[2].

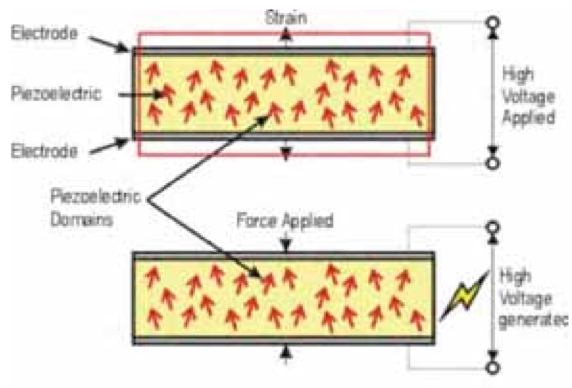

Figure 2: The piezoelectric effect.

2.2- Piezoelectric Use

While piezo-transducers are often used for low power applications, including electric lighters, sensors, and acoustics, their use in power generation is largely an understudied area of focus. The charge generated is typically quite low power, falling in a range of 15-20 microamps per cell. This presents a unique challenge in terms of energy storage, both from an efficiency and overall effectiveness perspective. ACT outlined several key requirement goals of optimization that were considered when working with piezoelectric elements. Then, a general schematic of the energy collection system was developed as seen below in Figure 3.

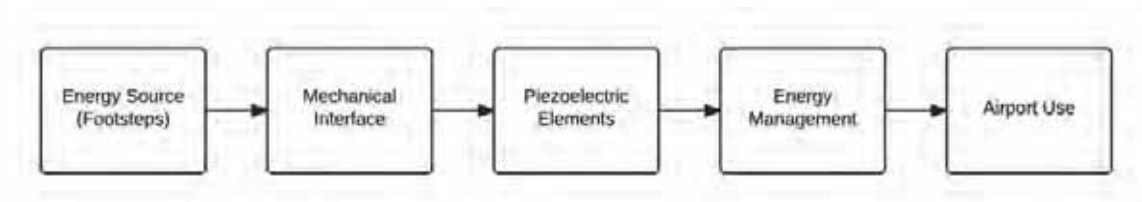

Figure 3: Energy collection system diagram.

The ideal system efficiently creates a mechanical interface between the source, footsteps, and the generating piezoelectric material. This suggests that the greatest amount of energy is focused on the transducers thus producing the largest possible output. ACT is confident in their achievement of such a system.

3- Summary of Literature

3.1- Piezoelectricity

Piezoelectricity describes the phenomenon of obtaining an electric charge in response to applied mechanical pressure onto certain materials. Those materials commonly exist in the forms of crystals, ceramics and various solids. The phrase is derived from the word *piezein*, which means *to squeeze* in Greek. When a piezo-element is under mechanical stress, its atomic structure is deformed, creating an unbalanced negative and positive charge within the material. Such deformation generates an instant spark of high voltage but low current. Therefore, the common applications for piezoelectricity concentrate on sensors and actuators, monitoring the slightest changes in applied pressure.[3]

Piezoelectricity was discovered in 1880 by the brothers Pierre and Jacques Curie through their experiment using crystals of tourmaline, quartz, and Rochelle salt. Numerous studies were performed on the technology leading to its first application on sonar. Currently, piezoelectric material can commonly be found in devices such as microphones, gas igniters, quartz clocks, and buzzers[4].

3.2- AC/DC Converter

Storage is one of the major concerns for any energy harvesting system, especially those with an inconsistent power output such as piezoelectricity. It is not efficient and safe to power applications directly by energy harvested from piezoelectric materials. The short burst of voltage implies that the operating duration only lasts for an instant and the high voltage reduces the equipment's life span. Therefore, a storage device is introduced as the middle agent to regulate the

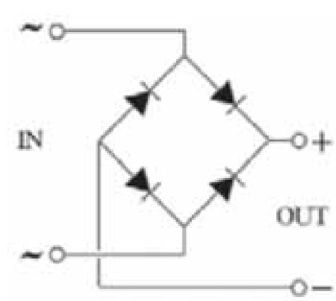

Figure 4: Diode bridge rectifier.

output voltage and save harvested energy for a later use with minimal dissipation. Since the targeted application uses direct current and piezoelectricity produces alternating current, the first component within the storage system is responsible for converting AC to DC output. The simplest method is to combine four diodes in configuration, as shown in Figure 4, to create a bridge rectifier[5].

4- Problem Solving Approach

4.1- Approach to Defining a Solution

A classical problem solving paradigm was used as the framework to investigate and structure the research and prototyping process. This framework consisted of 1. identifying the piezo-technology topic area; 2. exploring work completed to date on piezo-technology; 3. developing consensus on the requirements and specifications for the ultimate solution to meet competition and ACT goals; 4. defining various alternatives for meeting requirements; 5. selecting a candidate approach to move forward with for further development and prototyping; 6. fabricating the prototype; and 7. testing and evaluating the prototype.

When initially investigating the technical design challenge related to piezoelectric technology, multiple theoretical designs were brainstormed. The original design focused on using pre-manufactured energy harvesting chips to fulfill the electrical component of the design. This concept of using a pre-manufactured energy harvesting chip resulted from initial research conducted for the design challenge during the first several weeks of the fall semester. After extensive research on the pre-manufactured energy harvesting chip, ACT decided to focus on creating an entirely new, custom circuit to capture energy from a human step.

The primary reason for designing a new circuit rather than using a pre-manufactured chip was the complex nature of the manufactured chip. The manufactured chip required six inlets and provided two outlets. ACT's design called for a single input from the parallel piezoelectric transducer set-up and a single output to the energy harvesting device. Pre-manufactured chips were over-designed for the intended purpose of our system. It became a matter of simplicity- the newly developed, customized circuit was built for PECS and consequently worked perfectly for the system.

In addition to its simplicity, the customized circuit also proved to be less expensive than the pre-manufactured chip. Each pre-manufactured chip cost approximately $30, which when looked at from the full-scale perspective, became unreasonably expensive. With the pre-manufactured chip, the system would cost roughly $380 per square foot when scaled up, rendering the design useless. However, with components of the customized circuit readily available and far less expensive, the cost of the system vastly decreased. Due to the favorable cost analysis as well as the simplicity of the customized circuit, the alternative of using a pre-manufactured chip was rejected.

The primary reasons for addressing the design challenge with a custom designed circuit resulted from the agreed upon specifications and requirements for the prototype. Thus the design of PECS became the focus for ACT.

4.2- Design Focus

Major design areas of focus for the team included: consumer requirements, safety and risk, and cost. With a broad range of categories proposed by the ACRP Design Competition, ACT explored creative, unique, and feasible solutions to relevant energy harvesting issues. The team decided to focus on a solution that could be adapted to all types of airports, from high traffic to general aviation. The reason for this focus was to allow for the greatest number of airports to implement the technology. The PECS design is a relatively inexpensive and more efficient alternative to current flooring and lighting systems that consume large amounts of both money and energy. Collectively, the team's analysis tasks to demonstrate successful proof of concept for PECS included risk and safety assessment, engineering analysis, SolidWorks modeling, prototyping, and experimentation.

4.3- Research Process

There is a great deal of wasted potential energy in airport environments, both inside and outside. In the initial stages of research, other sources from which energy could be harvested were investigated. Sources of this energy include wind, sunlight, sound, and vibration. Initially, noise from aircraft was investigated and considered as a form of energy generation. The underlying theory is that noise is essentially a vibration: the louder the noise, the more vibration that occurs. The team began to investigate how much energy could be generated from the vibration of noise and how to store and use this energy. While innovative, the design direction ultimately proved infeasible because the amount of energy created by noise vibrations is not substantial enough to power devices with even the lowest energy consumption. In addition, if capturing the noise energy from planes taking off and landing were feasible, research indicated that energy would need to travel a long distance from the runway to inside the airport terminal before powering any application. The distance travelled dissipates the already low level of harvested power.

The lack of energy storage capability is a common challenge with not only noise energy but also many other renewable energy sources, including wind and solar energy. Without an appropriate storage system, energy harvested from those sources is not reliable given the limited availability of the source. Another reason why wind and solar energy were not used in this design is that the technology is well investigated and commonly implemented in different applications. As a result, the goal of innovativeness would not be achieved.

Alternatively, foot traffic is underused as an energy source since the technology to capture the energy and efficiently use it is not commonly practiced. It can be easily observed that the significant amounts of energy generated by human movement within high traffic areas are wasted. In daily activities, we continuously exert energy. Oftentimes, that source of energy is rejected for being insignificant and of no further use. However, given the appropriate technology, such as the piezoelectric effect, mechanical energy can be transformed into electrical energy capable of powering other applications. In terms of alternative designs, piezoelectric is a very innovative approach to the growing interest in generating renewable energy. As such, few designs have been previously researched and prototyped.

Piezo-harvesting technology is an emerging source of energy utilized abroad, specifically in the Netherlands where some dance clubs have adopted “Sustainable Energy Floors.” In Tokyo, Japan, a demonstration project at various train stations using piezo-technology to harvest energy is currently underway[6]. As passengers walk through the ticket gates, the pressure from their body weight generates electricity that is stored and used to power automatic ticket gates at the train station. However one specific difference between PECS and the demonstration project in Japan is the use of tiles instead of carpet. This difference can have a significant impact on three important considerations: cost, ease of installment, and weight. A tile configuration that is made of a plastic or other material is very heavy and therefore difficult to install. In addition, the use of carpet, as used in the design of PECS, suggests that the product can potentially be rolled or folded up and moved from one location in the airport to another, while the dance floors must be installed permanently. ACT believes that piezo-technology could greatly benefit the energy consumption management in higher traffic areas such as jet bridges or airport terminals.

4.4- Development Methods

PECS includes two major components: a harvesting system and a storage system. For the harvesting system, ACT decided between several different choices of piezo-elements available from major distributors. Through a comparison including productivity, availability, durability and price of all candidates, the team concluded that a round piezo-element commonly found in speakers is the most efficient. This is because the round elements are mass produced as components in loud speakers. Therefore, ACT can capitalize on the feature to minimize cost.

Initially, ACT investigated the actual application behind piezoelectricity. The team recognized that mechanical stress at a low level is sufficient to deform the piezo-element and thus produce an electric charge. However, plane stress cannot maximize the output energy from the transducer but rather a combination of shear and torsion. As a result, ACT developed a mechanical design that optimized the pressure from each step onto the piezo elements. The design includes two solid plates sandwiching 5 piezo pieces (a detailed explanation is found in the System Technical Analysis section).

However, storing the energy proved much more difficult because the piezoelectric material produces a high voltage and short lasting signal. Such characteristics indicate that direct use of the harvested energy is not recommended without a proper regulating device. The team purchased several energy harvesting chips produced by Linear Technologies, as shown in Figure 5. These chips are designed to take an inconsistent voltage, store it in a series of capacitors, and release it at a constant output of 3.3 volts. This output is not enough to trigger the lighting of an LED, so two or more chips are needed in series to produce the required output. However, through several experiments of different voltage values, ACT discerned that the chip is not a reliable method for storing energy because of inconsistent output voltage. As a result, ACT developed a different storage system that is more reliable, easier to duplicate, and more cost effective. The custom designed storage system includes a bridge rectifier, super capacitor, and current switch. This system will be discussed in more detail in the Electrical Components section of this paper.

Figure 5: Energy harvesting chips (Linear Technologies).

5- Safety Risk Assessment

ACT employed a thorough risk assessment to comply with the FAA Safety Management System Manual (SMS). The team has identified certain safety considerations that apply universally. The modern aviation system is characterized by increasingly diverse and complex networks of business/governmental organizations as well as increasingly advanced aircraft and equipment. According to AC No: 120-92A: Safety Management Systems for Aviation Service Providers, the important characteristics of systems and their underlying process are their safety attributes when related to operational and support processes. These attributes have safety requirements built into their design to provide improved safety outcomes. These attributes include: responsibility and authority, procedures and controls, process measures, and interfaces (ATOS). ACT followed AC protocols when analyzing the safety and risk of the system. As a result, the team has assumed responsibility for accomplishing required precautions, with the final PECS design to be distributed with clear instructions for airports to follow, providing organizational and supervisory controls on the carpet interface, measuring processes and products, and recognizing the important interrelationships between processes and activities within the airport as well as with consumers and other stakeholders. As directly stated by SMS principles, the four essential components of a safety management system are provided below[7]:

1. Policy – all management systems must define policies, procedures, and organizational structures to accomplish their goals
2. Safety Risk Management (SRM) – a formal system of hazard identification and SRM is essential in controlling risk to acceptable levels
3. Safety Assurance (SA) – once SRM controls are identified and in operation, the operator must ensure the controls continue to be effective in a changing environment
4. Safety Promotion – finally, the operator must promote safety as a core value with practices that support a sound safety culture

PECS complies with all SMS, FAA, and specific airport operations safety protocol and is designed with a factor of safety of 1.5

6- Description of Technical Aspects

6.1- Development of Design

The PECS fully functioning prototype was designed for a square foot of carpet and constructed using thermoplastic elastomer (TPE) for the bottom layer, high-density polyethylene (HDPE) for the plates housing the piezoelectric circuit on the middle layer, and commercial carpeting overlaid for the top layer. This layering can be seen in Figure 6. HDPE is designed to be a strong yet manageably ductile material. Longevity was a major concern when developing plans for the system prototype. The ACRP and FAA have a multitude of rules and regulations regarding airport equipment, installation, and lighting. Following regulation standards, the full-scale commercialized design will be made of HDPE to maintain structural integrity; manufacturing costs will decrease significantly with large bulk purchases of components. The commercialized version of the product's circuit will include an autonomous switch to control electrical output. The entire system will have carpeted material covering the individual tiles of the system. To demonstrate proof of concept, the prototype model has been designed, built, and tested for viability.

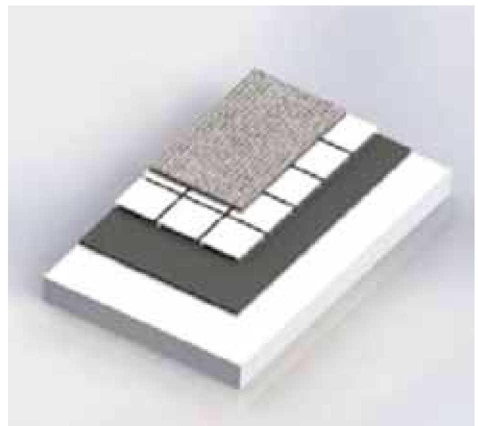

Figure 6: The layering of PECS. From bottom to top: subfloor, TPE, piezoelectric system, commercial carpeting.

The overall objective of PECS is to aid in the efficiency of the airport as well as to lower the annual operational costs. PECS can be theoretically implemented into any type of airport; it is inexpensive, easily maintained, cost-efficient, and uses a relatively simple electrical system to provide a marketable technology to airports.

6.2- System Technical Analysis (Mechanical)

The following two figures are SolidWorks 3D renderings of the assembly. Figure 7 shows the preliminary prototypes while Figure 8 illustrates an exploded view of the final 3in. by 3in. plate design.

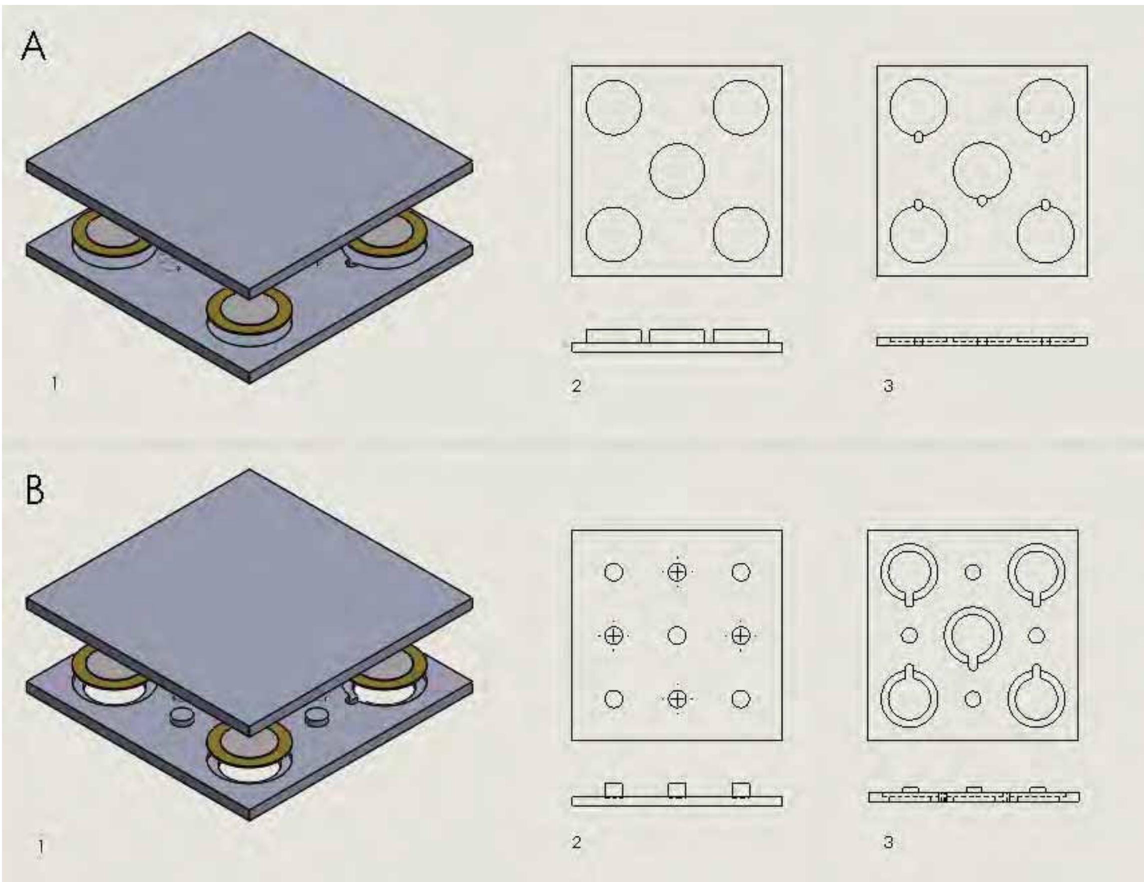

Figure 7: Exploded views of prototypes A and B.

Prototype A is the initial design that was 3D printed. One can see that the piezo-transducers are sitting flush, while in prototype B there is a section cutout below the piezo-transducers. This allows for a larger displacement of the transducers upon impact, thus increasing the voltage output. In addition, spring posts were added to Prototype B allowing the springs to be constrained in two directions and only move in the third (up and down).

ITEM NO.	PART NUMBER	QTY.
1	Bottom Piezo Plate	1
2	Piezo element	5
3	Spring	4
4	Top Piezo Plate	1
5	Impact Post	5
6	Spring Post	8

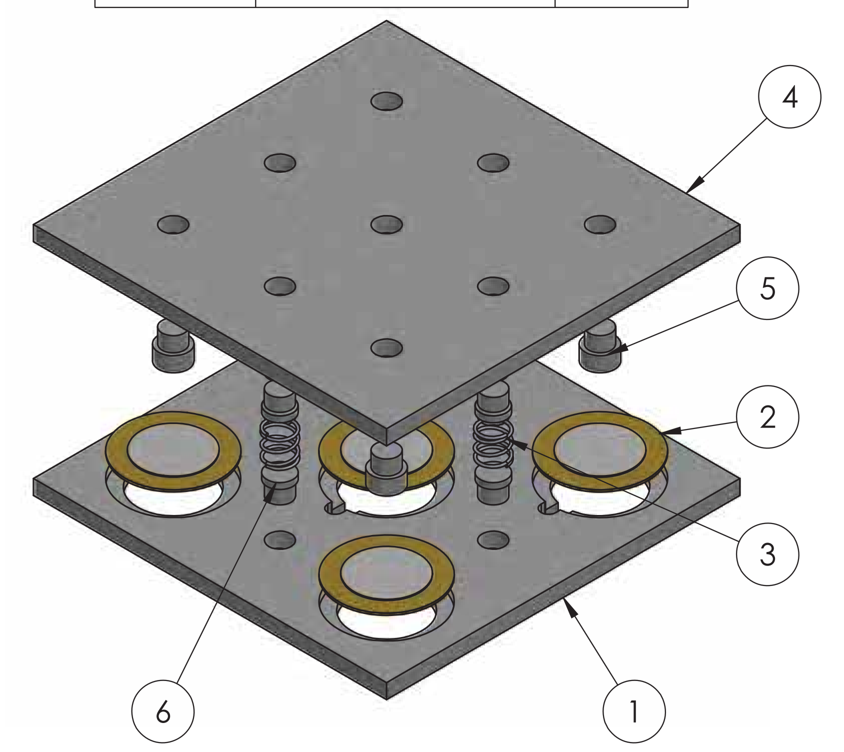

Figure 8: Exploded view of the final PECS 3in. by 3in. plate prototype.

The prototype design consists of two plates (3"x3") made of High Density Poly Ethylene (HDPE) machined using a CNC coding mill and CNC lathe. The bottom plate houses the piezo transducers, with small holes to allow wiring to pass through. There are four posts (d=0.22") on the top and bottom plates that act as attachment sites for the four springs. The top plate additionally contains five posts that act as impact points for the piezo-transducers. All of the posts were milled from an 8ft rod of HDPE (d=0.25”) using the CNC lathe. The posts are press fitted into the plates and plastic specific epoxy glue was used to provide more attachment to the plates. As the plates are stepped on, the impact posts hit the piezo-transducers. The springs are compressed and the spring posts act as the stopping points to prevent all of the force flowing through the impact posts to the piezo-transducers because they could snap if too much force is applied. The springs act as the restoring component of the system allowing the plate to be raised again.

6.3- Electrical Components

The designed PECS system utilizes simple circuitry to capture the voltage produced by the piezoelectric transducers, and then store the charge as effectively as possible. The primary challenge in this design was creating a system that would store a relatively low power signal, as quickly and efficiently as possible, while being limited to power-less components. Because of the low-current signal, the use of lithium batteries would not be effective, as charging times would be quite long and inefficient. Therefore, relatively high-value capacitors (4700 microfarads) are used in place of traditional batteries. Some conditioning is also required, as the transducers produce an AC signal that is not ideal for charging a capacitor. To remedy this, a full-wave bridge rectifier is placed immediately after the piezo-transducers. This produces a DC signal that more effectively charges the capacitors used, while also preventing back flow of current that would negatively affect the other transducers used. Two push-button switches, as presented in Figure 10, control the signal flow. When the capacitor has been charged fully, the switches are depressed, allowing charge to flow from the capacitor to the LEDs. Figure 9 shows the completed circuit schematic used for one tile.

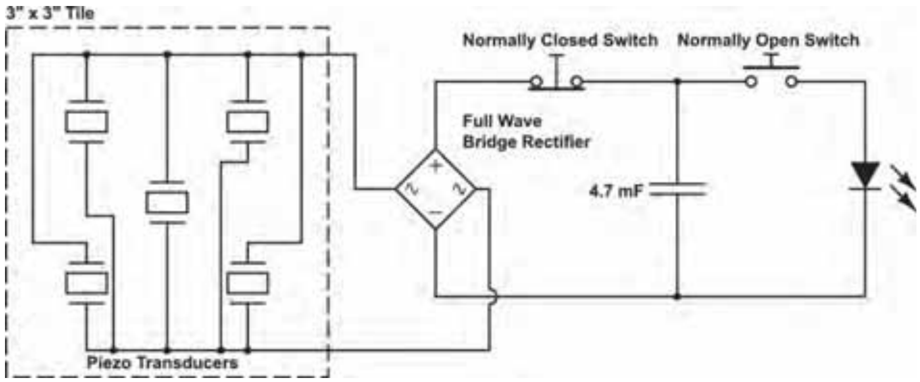

Figure 9: Circuit Diagram of one 3”x3” tile with connected load.

As illustrated in Figure 9 above, the transducers are arranged in a parallel configuration, which is the optimal design for storage purposes. Each transducer, shown in Figure 10, produces between 1.5-3 volts, though the current produced is on the order of a few milliamps. The voltage results from impact on an individual plate is presented in Figure 11. The peak voltage generated from this system is approximately 25 volts.

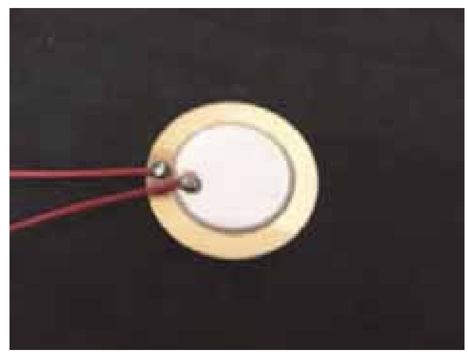

Figure 10: Piezoelectric disk transducer.

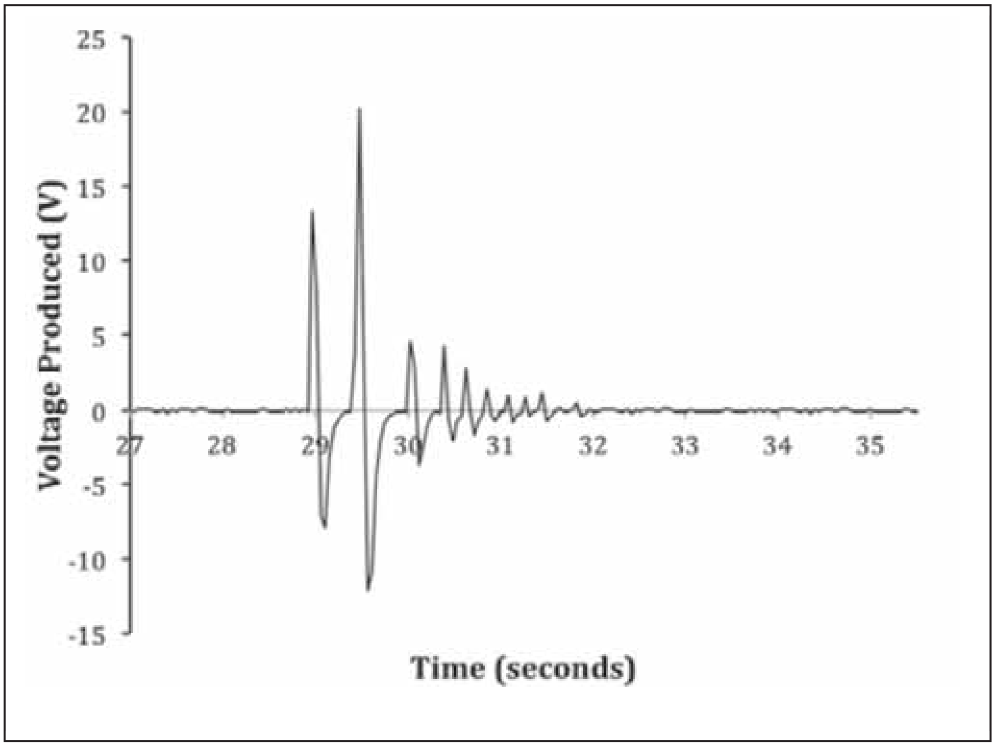

Figure 11: Voltage output of impact on one plate in PECS.

To maximize current to the greatest extent possible, which would then lead to faster charging times, the transducers are placed in parallel, effectively summing the current between all of them. In addition, this eliminates the problems that arise when not all transducers are activated. When at rest, the piezoelectric elements act as an open circuit, which, if in series, would prevent any signal from passing though when generated by previous transducers. The parallel configuration allows any generated signal to pass, regardless of the state of the transducers between the signal and the storage device. This parallel configuration is illustrated below in Figure 12, as well as series arrangement for comparison.

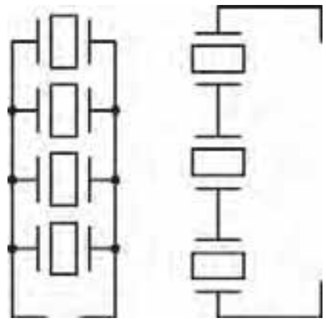

Figure 12: A comparison of parallel (left) and series (right) arrangement of piezo-transducers.

6.4- System Programming

While the current system operates without system programming, there is significant room for expansion into that area. Manual push-button switches control the current proof-of-concept, for testing and validation purposes. As seen in Section 6.3, Figure 9, the left-most switch is normally closed, allowing a signal to pass through to the capacitor for storage, while the right-most switch is open, preventing that charge from escaping to the LEDs prematurely. Once the capacitor contains sufficient charge, the switch orientations are reversed, allowing the energy in the capacitor to be fed to the load. Future expansion options include the addition of an Arduino microcontroller, which, while being powered by the system itself, would control the release of the signal from the storage devices. The Arduino would monitor the level of charge in the capacitor, and would, upon reaching a certain level, release the charge by sending a signal to a switching transistor. This could also facilitate the transfer of signal between capacitors so one would be charging while the others are providing power to the lights. This solves the problem of only having around 15 seconds of light from one capacitor as they could be instantly switched to provide a continuous source of light.

6.5- Engineering Analysis

A complete engineering analysis on all components of the design, including fatigue and failure analyses, material integrity, manufacturing processes, and motion studies was performed. The piezo-plates were designed taking all of the engineering analysis results into consideration. The springs, piezo-transducers, top and bottom plates, and posts were all tested under varying foot forces. Free body diagrams of each component were used to analyze such forces. An overestimation of forces was used to ensure integrity of the system would remain intact during long-term fatigue exposure.

6.5.1 Anthropometry Studies

The average body mass in North America is 80.7kg (177.9 lbf)[8], while the approximate index for the average mass of an obese male is 92kg (202lbf)[9]. The analysis was performed for both the average and maximum force considerations. A walking gait analysis was also performed to determine the reaction forces on the plates induced by the average person walking along the system.

To determine the maximum percentage of force induced on the plates relative to body weight, an approach measuring the center of gravity during various points of walking and then calculating the center of pressure (COP) was used. The COP is equal and opposite to a weighted average of the location of all downward forces acting on the plate. Experimental analysis determined the vertical ground reaction force will be 100% ±20% of body weight due to inertial forces while walking. During the final stage of a walking cycle (push off) the induced propulsion creates forces up to 105% of body weight[10]. The maximum factor of 120% of body weight is used in the force analysis to determine fatigue and yielding. The stress induced will be distributed across the 3in. x 3in. plates.

Utilizing the average weight of an individual of 180 lbs, the stress on the top plate is therefore calculated as:

$$\sigma = F/_A = {(1.2 * 180lbf)}/_{(3" * 3")} = \mathbf{24psi}$$

6.5.2- Stress Concentration

To understand how the force flows through the device, stress concentrations are measured[11]. An argument can be made for assuming that the load is relatively distributed over the entire plate due to the gait analysis across each 3in. by 3in. plate. Therefore the total area on the top plate will share an equal amount of the force. The force will flow through the spring and impact posts to the bottom plate, and distribute to the bottom plate spring posts and the piezo transducers. Stress concentration factors are considered in terms of the spring posts where the maximum stress can be expected to flow. A 1mm displacement on the piezo transducers was assumed to allow enough strain for inducing a voltage. This is the maximum deformation the piezo-transducer can endure without being permanently deformed. The ultimate tensile strength (S_{ut}) of HDPE is 3.43kpsi[12]. The part fabricated from HDPE material is considered highly notch sensitive, therefore the notch sensitivity value q = 1[13]. This value is then used to calculate the fatigue stress concentration factor.

$$K_f = 1 + q(K_t - 1)$$

Equation 1

The theoretical stress concentration factor, Kt, was calculated using a chart with consideration for the post dimensions and fillet radius. The peak concentration is displayed as an X in Figure 13.

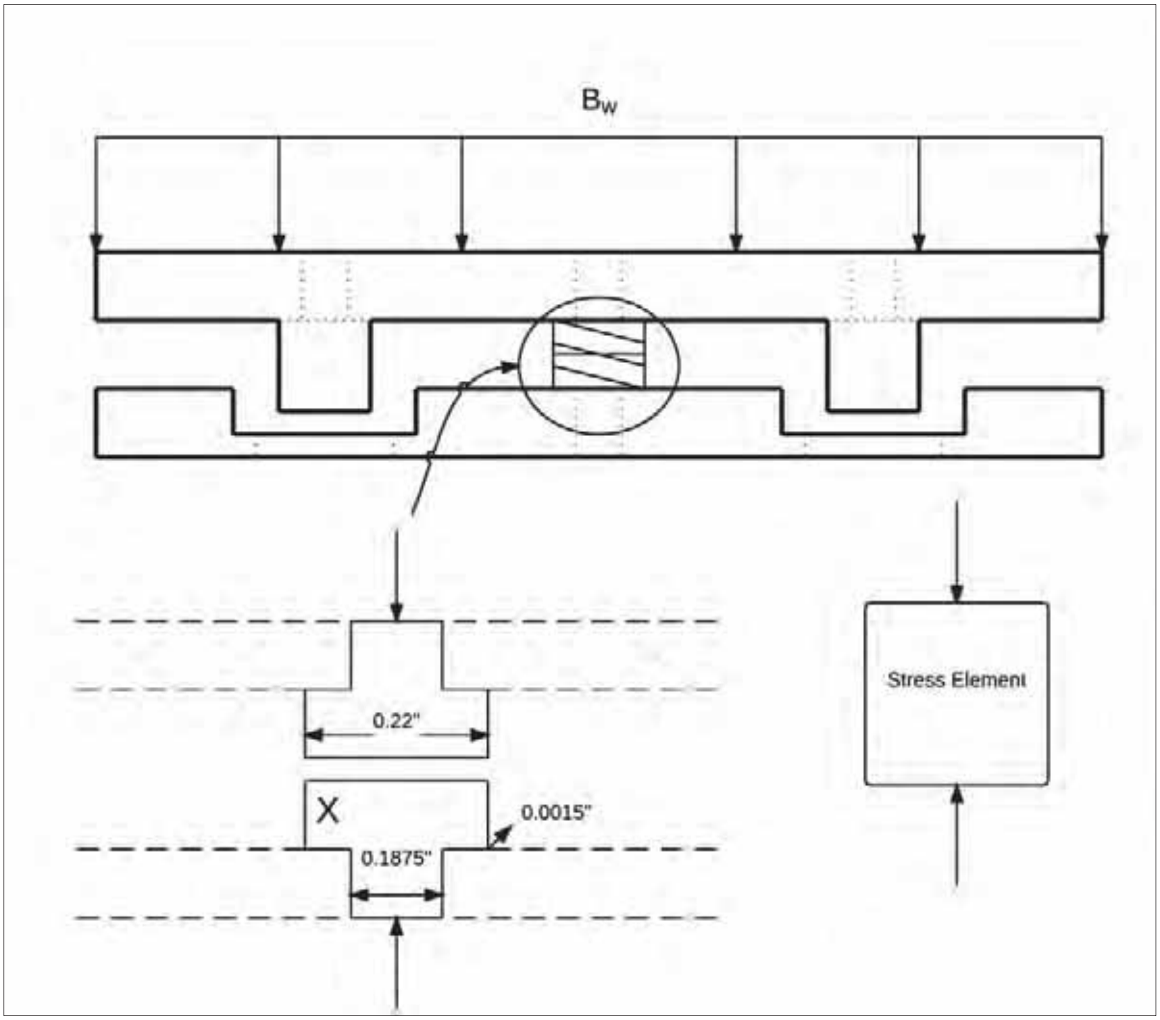

Figure 13: Schematic of the force analysis determining where max stress is concentrated

A stress element is assumed at point X where the largest amount of stress experiences pure axial loading as compression. The calculations in Figure 14 were performed for a person of 180lbs stepping on one plate.

Initial Conditions:

Average Bw in U.S. is 180lb

Majority of stress concentration will be experienced by spring posts

Five posts total, weight/post calculation:

$$= \frac{1.2B_w}{5\,posts} = \frac{1.2(180lb)}{5\,posts} = \mathbf{43.2}\,\frac{\boldsymbol{lb}}{\boldsymbol{post}}$$

Stress Concentration:

Shigley's Mechanical Engineering Design, 9th ed. used as reference:

$$\frac{r}{d} = \frac{0.015}{0.1875} = 0.08$$

$$\frac{D}{d} = \frac{0.22}{0.1875} = 1.173$$

From Figure A-15-7 the theoretical stress concentration:

$$K_t \backsimeq 1.74$$

Fatigue Stress concentration:

$$K_f = 1 + q(K_t - 1)$$
$$q = 1$$
$$K_f = 1 + 1(1.74 - 1) = 1.74$$
$$\boldsymbol{K_f = K_t = 1.74}$$

Endurance Limit Modifying factors:

Surface factor, K_a:

From Table 6-2:

$$a = 1.34\,, b = -0.085$$

Ultimate Tensile strength of HDPE:

$$S_{ut} = 3.43\ kpsi$$

$$K_a = 1.34{S_{ut}}^{-0.085} = 1.34(3.43)^{-0.085} = 0.664$$

Size factor, K_b:

For axial loading → K_b=1

Load factor, K_c:

For axial loading → K_c=0.85

Endurance Limit of Test Specimen:

$$S'e = 0.5\,S_{ut}$$
(When S_{ut} < 200kpsi)
$$S'e = 0.5(3.43kpsi) = 1.71kpsi$$

Endurance limit of post:

$$Se = K_a K_b K_c S'e$$
$$Se = (0.664)(1)(0.85)(1.71kpsi) = 0.966kpsi = \mathbf{966}\boldsymbol{psi}$$

Fatigue Calculations:

Uniaxial, repeated fatigue loading characteristics:

$$\sigma_{min} = 0$$

$$|\sigma_a| = |\sigma_m| = \frac{\sigma_{max} \pm \sigma_{min}}{2}$$

From above:

$$F_{max} = 43.2lb$$

Max stress:

$$\sigma_{max} = \frac{F_{max}}{A} = \frac{43.2\ lb}{\pi/_4\,(0.22in)^2} = 1136\ psi$$

Theoretical Alternating and Mean Stresses:

$$|\sigma_{ao}| = |\sigma_{mo}| = \frac{\sigma_{max}}{2} = \frac{1136psi}{2} = 568psi$$

Actual Alternating and Mean Stresses:

$$\sigma_a = K_f\sigma_{ao} = 1.74(568psi) = 988.3psi$$
$$\sigma_m = K_f\sigma_{mo} = 1.74(568psi) = 988.3psi$$

Factor of Safety against Fatigue:

$$1/_n = \frac{\sigma_a}{Se} + \frac{\sigma_m}{S_{ut}}$$
$$1/_n = \frac{988.3psi}{1730psi} + \frac{988.3psi}{3430psi} = 0.859$$

$$\therefore \boldsymbol{n = 1.16}$$

Figure 14: Calculations for fatigue stress and factor of safety when a 180lb person steps on one plate.

The same analysis performed above can be replicated for a 350 lb. person stepping on one plate; the results are presented in Table 1.

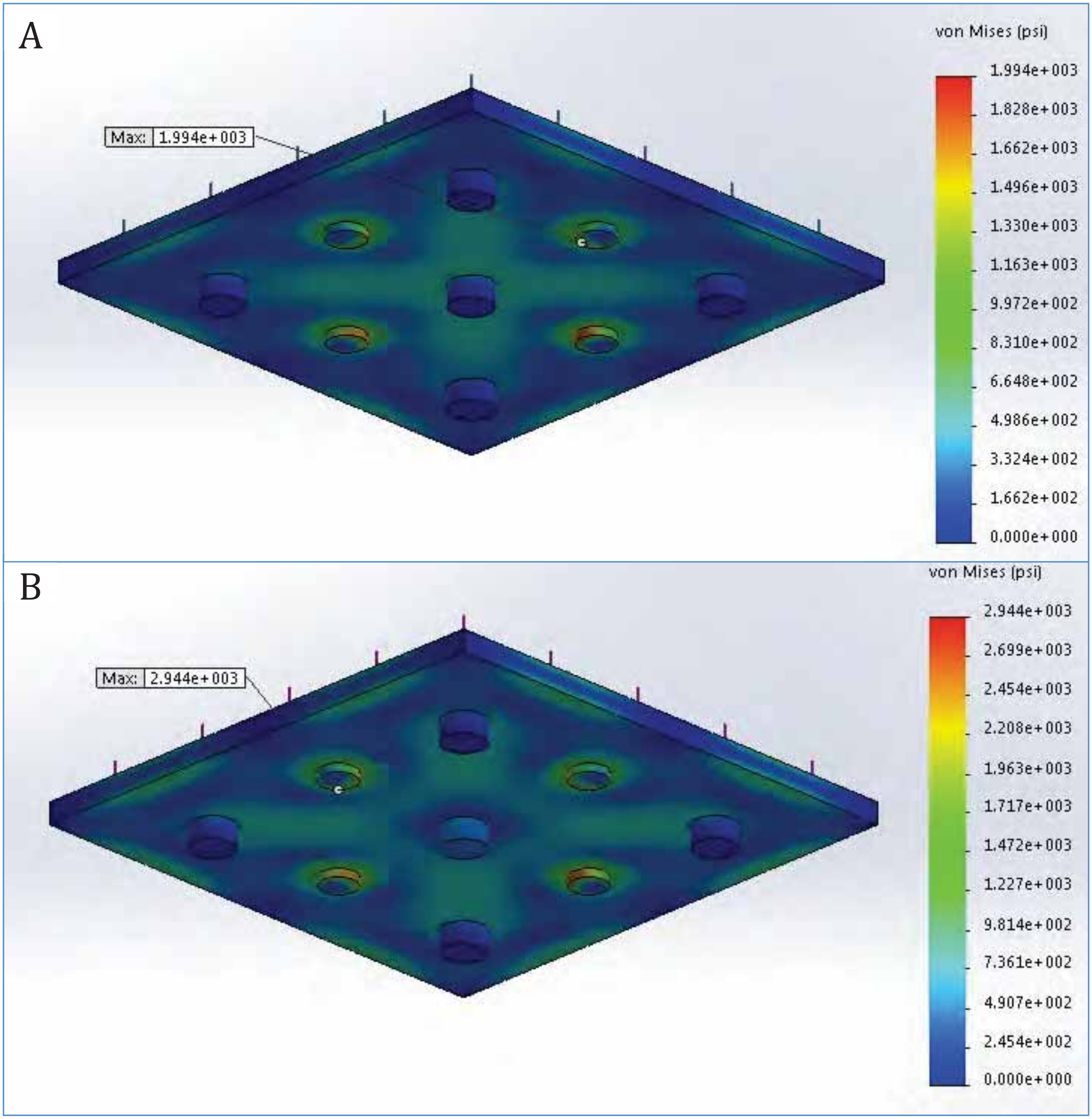

Figure 15: SolidWorks analysis to determine the maximum stress caused by (A) a 180lb person and (B) a 350lb person.

A computational model was also created utilizing SolidWorks' static analysis simulation. An applied distributed load of 180lb was induced on top of the entire 3in. by 3in. system and the stresses were calculated using a mesh analysis. A SolidWorks static simulation performed on the system determined the maximum stress induced on the plate assembly when stepped on by a person of average weight (180 lbs.) to be 1984 psi, and a person of heavier weight (350 lbs.) to be 2944 psi, both of which can be seen in Figure 15. The numerical and analytical results are compiled in Table 1.

Table 1: Factor of safety and maximum compressive stress tabulated results.

Weight (lbs)	Computational		Analytical	
	Compressive Stress (psi)	Factor of Safety	Compressive Stress (psi)	Factor of Safety
180	1984	2.10	1136	1.19
350	2994	1.37	2209	0.63

During initial testing of the 3D printed prototype, failure was found to occur at very specific stress concentrations on the plate due to the stepping force, namely along points of contact between the plate and posts. This observation helped with determining specifications while performing the analysis for the actual milled parts. As such, those were the points considered when performing the fatigue analysis as seen in Figure 14. According to standard airport operations, the minimum factor of safety to comply with FAA standards is 1.5 against fatigue when external loads are induced on the structure[14]. Therefore the plate complies with these design criteria for the average weight; however, modification to design, more specifically the material, may need to be made to allow for a larger range of weights on the plate.

7- Description of Interactions with Industry

In an effort to collect information and feedback from industry experts, the team conducted an electronic survey to introduce PECS to airport management and facility design decision makers. The survey was sent to twenty U.S. airport experts listed on the ACRP design competition website representing a range of airport sizes. The response rate was 73 percent. Valuable insight was provided by many industry experts from various backgrounds. The survey consisted of questions about challenges related to the design and implementation, cost efficiency, and overall impressions and interest.

As expected, cost was a major concern for respondents. When asked if there were any foreseeable challenges in the implementation of this technology in an airport, one respondent replied,

"The challenge with regard to these type[s] of technologies is cost. Currently, finding funds for any airport improvement project is a challenge. Airport infrastructure has been reported as somewhat poor by the American Society of Civil Engineers. The Federal Aviation Administration (FAA) provides grants for many projects but there is simply not enough funding for all needed or wanted improvements. If one could find a way for your concept to be a net gain as opposed to a net zero technology then the application of the technology would have a higher chance of being implemented."

Another respondent offered his assessment on the cost challenge:

"If you have a way of introducing a passive energy generating technology in the airport environment it should be of interest. The big general concern is the cost-benefit component: how do the potential costs of the system compare to alternative means of

generating energy? Are the ancillary costs of sourcing conventional energy outweighed by the benefits of this source? Could generated energy be stored in batteries for when there is less foot traffic?"

Cost was identified as a challenge not only from the manufacturing perspective cost-benefit trade-offs but from a life-cycle analysis as well, as another respondent pointed out:

"For any product, you should look at the life cycle for the overall cost- this would include not only the manufacturing and installation, but also the maintenance and disposal of the product at the end of its useful life."

ACT took this input into consideration when selecting materials to use and how many electrical components per square foot would be necessary. Overall, the cost of the carpet is estimated at roughly $20/SF, as presented in the Financial Analysis section. This represents a net gain when compared to current lighting and flooring costs.

Other input from respondents focused on the durability and life of the piezo-carpet. Some respondents, when asked about foreseeable challenges, replied saying,

"The system would have to be reliable and stand up to a high traffic environment. The carpet…would need to be as good or better than conventional flooring systems."

And

"How durable is the technology? Is lighting available if there is no foot traffic? Will it stand up to luggage, spills, and other challenges of the airport terminal environment?"

ACT again took this into consideration when deciding what materials to use in the full-scale commercialized design. The HDPE is durable but slightly ductile, allowing a life-cycle that is as good as or better than commercialized design, as suggested by the respondent.

The majority of respondents, when asked if they would support this technology for airport installation, responded positively. Many viewed PECS as a technology with broad application possibilities and provided support as long as the cost of the carpet will be comparable to traditional installations, which ACT predicts it will.

"I would support the technology provided costs and durability were comparable to or better than traditional installations. Electric utility cost is a major expense center for airports. Every bit of energy efficiency that can be implemented helps to reduce operating costs and in turn lowers fees that must be charged to airlines and passengers."

Finally,

"Yes, I would love to see it work. Frankly, if this was really possible, it is a huge winner in many, many applications. Just show it is viable, and your design proposal should be quite well received."

Which such positive feedback, ACT predicts that PECS will gain even more support during further development and be a viable source of energy for airports, as well as a cost-reducing investment.

8- Description of Project Impacts

8.1- Commercial Potential

The current design is a benchmark scale of 1/60. The commercialized product will ultimately be a system that can be placed in various areas throughout the airport including the jet bridge, security line, and baggage drop off. Because the prototype is a fully functional 1ft. by 1 ft. system, and the commercialized product builds on the 1ft. by 1ft. sections, PECS can be retrofitted to virtually any size or location. Specifically for a jet bridge, the system is proposed to cover a 5ft. by 50ft. span.

Many analyses were performed to determine the potential of scaling up our design. By purchasing materials in bulk and manufacturing on a larger scale, this design will prove cost-effective in high traffic airport areas.

8.2- Manufacturability

The system was manufactured in Roger Williams University machining labs by ACT using a CNC Lathe and CNC Mill. Specifically, the posts and plates were fabricated while the springs and electrical components were purchased from various suppliers. In the proof of concept 1ft. x 1ft. array, there are a total of 24 plates and 156 posts that were machined in-house. This proved a time-consuming effort; however, it was the most ideal in terms of feasibility, material choice and availability, testing, and technical knowledge. The prototypes were originally created using 3D printing. While this was the least work intense option, the material available failed soon into testing and printing one plate took about 2.5 hours. After the first attempt using a 3D printer, manufacturing moved to a CNC mill and lathe to fabricate the HDPE plates and posts. This material is much stronger against failure and takes less time to complete. In addition, it can be replicated at any time using the G-code created for the programming of the CNC machine, an example of which can be seen in Figure 16. Electronic components such as capacitors, switches, and LEDs are commonplace items that can easily be purchased in bulk.

```
(FAA-turning-from0.25to 0.22 to 0.1875)
(Starting-from-diam1/4-down-to-diam0.22down-to-diam3/16)
(L3/16=A-L1/4=B)
(Calibrate-diameter-before-start)
(Setz=0-at-start-of-rod-and-x=.3125)

N001 G40 G18 G80 G50
G90 G20 G53
N010 F10

N030 G01 Z0.1
N031 M03 S600
N035 F5

N065 G90
N070 G01 X.265
N075 G91
N080 M98 P1000 L19
N081 G90
N082 z0.1 x0.2275
N083 G91
N084 M98 P2000 L19

N085 G90
N086 G01 z0.1
N090 G01 X0.275
N100 F10
N105 z2.0
N110 T0303
N115 z-0.645
N115 F0.1
N120 G01 x0.10
N125 F10
N130 G01 x0.3
N135 G01 z2.0
N136 T0101
N137 G01 x0.0
N137 G01 z0.0
N140 M2

O1000
N1000 G01 X-.005
N1010 G01 Z-.295
N1015 F10
N1020 G01 X.01
N1030 G01 Z.295
N1040 G01 X-.01
N1045 F5
N1050 M99

O2000
N2000 G01 X-.005
N2010 G01 Z-.225
N2015 F10
N2020 G01 X.01
N2030 G01 Z.225
N2040 G01 X-.01
N2045 F5
N2050 M99
```

Figure 16: Example of G-code using for machining the CNC lathe spring posts.

8.3- Testing

To ensure a fully functioning system, testing was carried out on the prototype. While developing the storage circuitry, a power source was used in lieu of the piezo-transducers. Once the storage switch system was created, the piezo-transducers were then integrated into the system. To understand the full voltage potential of the piezo-transducers, multiple measurements were taken measuring the output voltage of a plate containing five transducers. Maximum spikes of voltage reached up to 25V when the plate experienced a short burst impact of force, as seen in Section 6.3 Figure 11. The current ranged from 15 to 20 microamps due to impact. This allowed ACT to optimize the design in terms of power output.

8.4- Operation

The system is easily operated by airport facilities workers. A simple switch is used to activate the system, similar to turning on a light switch. One of the instrumental design considerations during this process was easy installment of the system, which required a lightweight, moveable design.

8.5- Maintenance

A fatigue analysis was performed to estimate the total number of cycles the system will survive. An instruction booklet will be provided with the final design, including a list of where parts can be purchased, as well as a troubleshooting section. Another important consideration in terms of maintenance is the protection against wear and weathering. While the system will remain indoors, individuals stepping on the carpet will not. The carpet material was chosen based upon its water resistance.

8.6- Financial Analysis

A realistic approach to the cost analysis was achieved through a cost/benefit determination for the team's design. The following itemized budget table lists parts and their costs.

Table 2: Bill of materials with associated cost including overall square footage.

BOM Level	Component	Description	Quantity	Units	Cost
0	12"x12" System		1	each	**$20.76**
1	Zip Ties	1/8" x 8" tie	14	each	$0.70
1	Carpet	Standard carpet	1	sq. ft.	$3.50
1	LED Strip	12 V Max; 3 Meter Strip	12	inches	$0.49
1	3"x3" Tile Top	CNC Cut HDPE	12	each	$3.17
1	3" x 3" Tile Bottom	CNC Cut HDPE	12	each	$3.17
1	Posts	0.25” Dia. HDPE	6	feet	$4.00
2	Piezo Transducer	3/4" Disk Transducer	5	each	$1.80
2	Spring	0.22” x 0.25”	4	each	$0.48
	Diode	Stnd Rectifying Diode	4	each	$0.60
2	Capacitor	4.7 mF Capacitor	1	each	$1.49

Considering financial goals and manufacturability in unison will allow ACT to optimize the design to reduce costs while also decreasing manufacturing time. This can be achieved during production of the full-scale model, when stock material such as the HDPE sheets and rods, springs, and piezo transducers can be bought in bulk to decrease price.

8.6.1- Cost-Benefit Analysis

Energy consumption is a major issue at airports, especially those with higher traffic since energy is required to maintain most airport functions. With the increasing cost for carbon-based electricity production along with its harmful impact on the environment, renewable energy emerges as a compelling solution. Advantages for such a system include minimal additional costs in addition to installation and maintenance, improvement in environmental quality, and renewable energy sources[15].

A detailed cost analysis of an innovative system requires multiple assumptions and standards, which the team developed. To begin the cost savings analysis, the team measured and averaged output values for a single tile, as follows:

$$\textit{Average Voltage Output per Tile per Step} = 25.0\ \textit{Volts}$$

$$\textit{Average Current Output per Tile per Step} = 20\ \textit{microAmps}$$

Therefore, the Average Power per Tile per Step is given by:

$$P_{Tile} = VI = 25.0\,V * 20\mu A = 0.0005\,Watts$$

Expanding this value to a 3,000 tile, 5ft. x 50ft. system:

$$P_{System} = 0.0005\,W * 3000 = \frac{1.50\,\frac{Watts}{Step}}{System}$$

Therefore, if every tile were activated by one pulse, or step, the entire 5ft. x 50ft. test system would produce 1.50 Watts of power. To more accurately present a realistic interpretation of these results, it was assumed that there is, on average, 30 steps on each tile per minute during a boarding or egress period. Therefore, the power generated by the system in one minute is given by:

$$P_{System} = 30\,\frac{steps}{Minute} * 1.5\,\frac{Watts}{Step} = 45.0\,\frac{Watts}{Minute}$$

To effectively compare energy costs versus energy generation, this value was converted into Kilowatt-hours, the standard pricing value for electric power. To accomplish this, the team assumed that the jet bridge was in use for 60% of each hour, or 36 minutes. Therefore:

$$P_{System} = 45.0\,\frac{Watts}{Minute} * 36\,Minutes = 1.62\,kWh$$

Assuming the jet bridge is active for 15 hours a day, 365 days a year, the annual power production is given by:

$$P_{System,Yearly} = 1.62\ kWh * 15\ \frac{hr}{day} * 365 \frac{days}{year} = 8869.5\ \frac{kWh}{yr}$$

To determine the annual cost savings for airports, a price of $0.15/kWh was used[16].

$$Annual\ Savings = \frac{\$0.15}{kWh} * 8869.5\ \frac{kWh}{yr} = 1330.4 \frac{dollars}{yr}$$

This cost savings is calculated for one jet bridge installation. To fully examine the cost benefits, the actual cost of system production and installation is calculated. As shown in Table 2, the cost per square foot is approximately $21.00. For a 5ft. x 50ft. system, with minimal installation cost due to the roll out feature of the system, the total cost for one complete system is given by:

$$Cost = 21 \frac{dollar}{ft^2} * 250\ ft^2 = 5250 \frac{dollars}{system}$$

The net present value, used to determine both the breakeven point and the overall return was calculated using a seven-year service life and a 3% discount rate. The NPV considering initial investment of $5,250 and annual savings of $1,330 was calculated at $3,036. Conventional payback for the project occurs at the end of the fourth year.

9- Conclusions

PECS is intended to actively use the energy output of a human step to illuminate overhead lights on a jet bridge. The implementation of this system will mitigate airport operating costs and positively impact the environment. The savings accrued from PECS will increase each year and the system has incredible potential for growth, with many uses for the energy harvested through the system. For both high traffic and general aviation airports, PECS will have a positive impact on both the environment and operating costs.

PECS is an affordable and sustainable concept addressing society's need for a sustainable future with next generation technology. The system was created considering a variety of technical input and opinions from airport industry experts. It is based on a totally new, customized electrical circuit and layered carpet design to deliver efficient and self-sustaining energy to imbedded LED lights, and potentially other low-energy needs. As airports begin to implement PECS, they will be able to lower airport operating costs while simultaneously supporting a "green" environment.

ACT expects that the simplicity, affordability, sustainability, and efficiency of PECS will provide reductions in airport operating costs and a self-sustaining energy system. The benefits of PECS and its ability to conform to existing flooring conditions and FAA regulations will provide a feasible and marketable product for commercial development.

Appendix A- Contact Information

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Appendix B- Description of Roger Williams University

The principles and philosophies of Roger Williams University date back to our namesake, Roger Williams. Founder of the State of Rhode Island and Providence Plantations, Roger Williams was the first major figure in colonial America to forcefully argue the need for democracy, religious freedom and understanding of America's native cultures.

Roger Williams University is an independent, co-educational institution with a focus on undergraduate learning, paired with strong, related master's degree programs. The University is also home to Rhode Island's only law school. The mission of the School of Engineering, Computing and Construction Management is “excellence in undergraduate education.” The entire focus of faculty, staff and support resources in the School is on success of the student in an undergraduate program.

Roger Williams University School of Engineering, Computing and Construction Management offers a nationally recognized ABET accredited B.S. in Engineering program, an ACCE calculus/physics based B.S. in Construction Management program and a B.S. in Computer Science program. Undergraduate engineering students may choose among specializations in civil (structural or environmental track), mechanical, electrical, computer, or a custom-designed engineering track. Approximately 20% of all engineering students graduating from Roger Williams University immediately enroll in graduate school with many of these students accepted directly into Ph.D. programs. Five years after graduation, 65% of the school’s engineering graduates are either enrolled in a graduate program or have already completed one.

What is unique about the Engineering program is an underlying philosophy valuing a multidisciplinary approach to earning a professional degree, or education of the whole person. System-level thinking while achieving competence in specialized areas of engineering, construction management and computer science is stressed. All students graduating from the Engineering program are excellent communicators both in their written as well as verbal skills. Team exercises and projects are incorporated into all classes. The programs in the School of Engineering, Computing and Construction Management at Roger Williams University exist in an educational infrastructure that is flexible in its ability to address industry needs with regard to characteristics required in new graduates.

Appendix C- Non-University Partners

ACT dealt with many various airport experts. These experts were contacted via the expert advisors list under the resources provided by the competition website. The respondents provided a depth to the project that would not have otherwise been achieved. Through their replies, the respondents showed their professionalism and knowledge in addition to their support of the project. Their backgrounds varied across the four technical design categories, which allowed ACT to gain a thorough and multi-faceted perspective on PECS. These industry experts truly gave PECS valuable input and support to continue its growth to a full-scale product.

Appendix E- Evaluation of Educational Experience

Faculty Advisor – Dr. Linda Ann Riley

The Airport Cooperative Research Program (ACRP) provides a valuable learning experience for all students that participate. This is especially the case for the team that worked on the PECS project because all four of the undergraduate students will be attending graduate school in fall, two entering a Master's program at Cornell and University of Edinburgh and two entering directly into Ph.D. programs at Tufts University and Virginia Tech. The nature of the competition allows students such as this team to stretch their intellectual boundaries as undergraduates and go beyond what they have learned in the classroom. Because of its open-ended nature, it provides the opportunity for students to build a technical and expert mentor team that ultimately guides their solution. However, again as in the case with this group, there becomes a time in the second semester of work where the students have truly become the experts on the technology and application. As faculty, this is the ultimate measure of our success.

The competition provides an excellent platform for the senior engineering capstone design project in that the open-ended nature of the challenge fits perfectly with the learning objectives of the class. The challenge allowed the team an opportunity to study new subject matter and apply their past and new knowledge to solving and addressing an airport challenge.

The students faced several challenges with respect to this project. First, they are all mechanical engineers. Their ultimate solution required not only a depth of knowledge in mechanical engineering and testing, but also electrical engineering. All four students had basic exposure to electrical engineering but to successfully complete this project required a great deal of additional study and experimentation in the electrical realm. A second challenge is that this technology has previously proven very expensive to implement. The business case was very difficult to make for using this energy harvesting technology in real applications. Consequently, there were very few technical experts to advise the group since it is so infrequently implemented. In addition, off the shelf products were too expensive to use in fabricating the system from the perspective of making the business case. That led the students to create an entirely new approach to an energy harvesting circuit that reduced the price of the system dramatically. Finally, as is expected with a group of highly dedicated and intelligent students with backgrounds in mechanical engineering, they were very uncomfortable with the unknown. They had difficulty in making informed assumptions for the purpose of energy generation estimates. Throughout their college careers, most if not all textbook learning involves an exact answer that is either right or wrong. That is another reason this competition proves to be such a valuable experience, because it forces students to consider grand challenges that many times involve making assumptions to deal with the unknown.

In the future, I see continued participation by RWU in the competition. I feel that this competition is one of the best defined from the perspective of expectations, deliverables and evaluation metrics. In addition, the expert resources made available for students and overall administration of the competition is outstanding. There are no suggestions that I can make with respect to improving the competition. Unfortunately I will be retiring from teaching this year but hopefully my colleagues will continue on with the tradition of RWU's participation.

Undergraduate – Hy Dinh

Through the ACRP competition, I have had the opportunity to develop skills that are necessary for real world situations and strengthen the knowledge acquired from my undergraduate journey. The project provides a unique learning experience that I would not have been exposed to in a traditional academic course. In the initial stage of designing the project, we stumbled upon multiple interesting topics since the competition is open-ended. Through numerous discussions among the team and our mentors, we evaluated every proposal in detail with a focus on the applicability and innovative aspects. We finalized on undertaking the task of a piezoelectric harvester which, in fact, is challenging for our team specifically because important components of the desired system are extensively electrical-related while our team consists of only mechanical engineers. We often faced problems which we had no prior knowledge. To overcome these challenges, we individually trained ourselves through various means to be proficient in the piezoelectric technology as well as other electrical components. Furthermore, I found that interacting with professionals in the airport industry was extremely helpful. Not only did they contribute in refining the project through suggestions on applications and items that we did not consider, but they also provided positive feedback. We greatly appreciate the interaction with the industry. With completing this project, I have developed more technical skills and knowledge in an area that I never came across before. The competition also matured my teamwork and communication skills which are important for my future career.

Undergraduate – Emily Field

The ACRP design competition absolutely provided me with an invaluable learning experience. This process gave me the opportunity to not only excel and expand my knowledge in engineering design but also significantly improve my research and report writing abilities. I am very grateful to have participated in this design competition.

The primary challenge ACT experienced involved understanding the technical knowledge surrounding electrical components needed for storing energy. ACT was able to overcome this challenge by gaining advice from experts in the field, including electrical engineering professors as well as conducting numerous analyses of the electrical technology by creating circuits and understanding the various components involved.

The development of our hypothesis began with a mutual interest in studying energy efficiency in Airports. We eventually came upon utilizing piezo technology when we recognized the lack of research surrounding this phenomenon and therefore its potential for innovativeness in energy harvesting.

The utilization of industry knowledge proved to be invaluable in terms of the design process. More information was gained with regards to design criteria such as cost benefit, manufacturability, safety factor, and ease of installment due to our airport interactions.

Participating in the ACRP design competition allowed me participate in researching a technology that is relatively unknown. Thus I was able to gain a better background on the research process that I will encounter as a graduate student next year. Specifically I will be studying renewable energy systems, so this process was very much beneficial in terms of the content I will be pursuing in graduate school. This process also included becoming more affluent in the process of writing a technical research paper.

Undergraduate – Andrew Hannigan

The FAA design competition provided an extremely meaningful experience for me, and greatly improved not only my technical prowess, but also the soft skills that are necessary in a real world environment. This was unlike any other experience or class that I have had before, and I am thankful that I was able to participate in it.

The team faced several challenges while undertaking this design challenge, the first being a relative lack of knowledge of electrical systems. All members of the group are mechanical engineering specializations, and the project is very electrical. Although this may have thrown us in the deep end at first, it proved to be useful in the long run, as we are now proficient in both electrical and mechanical areas.

Our hypothesis was formed largely around a gap in technology that we saw great potential in. Piezoelectric transducers are used for many standard applications, but rarely seen as part of an energy generation system. This sparked our interest, and we saw an opportunity for design.

The industry participation was extremely helpful, and helped us determine the focal points that the design should be shaped around. The feedback was not only quite positive, which boosted morale, but also very informative. It was not only appropriate, but perhaps required that we get input from these professionals.

This project has greatly improved my communication skills, which is just as, if not more, important than technical ability. This alone, not to mention the vast technical knowledge and experience gained, has positively impacted my growth as an engineer.

Undergraduate – Kristen Tetreault

The ACRP Design Competition provided a meaningful learning experience for me. Personally, this competition became the culmination of my entire educational experience at Roger Williams University; it was the opportunity to compile all that I had learned over the past four years into one design project. In addition to using the knowledge garnered from previous classwork, the competition also provided the opportunity to work on communicating professionally and effectively. Perhaps one of the most important challenges the team overcame was gaining the technical knowledge of piezoelectricity to fully understand the technology and become experts on the topic. To overcome this challenge, an abundance of research was done prior to making any design decisions. Once the team felt comfortable as experts on piezoelectricity, the design really came together. After completing the prototype, we felt as though we really created something invaluable to not only ourselves but to the ACRP competition and airports collectively. This feeling was confirmed after receiving incredibly positive feedback from multiple airport experts. Talking to and working with these industry professionals was another great learning opportunity garnered from the competition. Many of these experts pointed out items we previously had not thought about, or those which needed more work. Interacting with those professionals proved crucial to the project, which showed how important it is to receive feedback on a potential design from experts in the intended field. This, and everything else I have gleaned from participation in the ACRP Design Competition, will certainly help guide me through the next few years as I pursue my Ph.D. in graduate school and long into my professional career as well.

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