College-Level Multi-Step Energy Conversion Efficiency Experiments Should be Decomposed for High School Deployment

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Abstract

Energy Engineering Laboratory Module (EELM™) pedagogy posits that energy is a topic ubiquitous, germane, and applicable to all Science, Technology, Engineering, and Mathematics (STEM) fields. Therefore, energy-focused hands-on laboratory experiences can be developed for successful seamless insertion into any STEM course. But is this hypothesis true?

A teaching laboratory experiment is described that demonstrates multiple energy conversions with capability to measure output at each step. This experiment was intended for use in a college-level introductory thermodynamics course, but it was implemented without modification in an Advanced Placement (AP) Physics 2 high school class to determine viability for a secondary education audience. This instance represents the first time a teaching lab apparatus employing the EELM™ design approach was deployed in a high school.

The experiment harnesses chemical energy contained within a candle, which is converted to thermal energy via combustion. The candle flame heats the hot side of a thermoelectric (TE) generator whose cold side is simultaneously cooled via ice water reservoir. The TE Generator is a solid-state heat engine converting thermal energy to electrical energy, which powers a DC motor. The motor lifts a small mass from the ground imparting potential energy. The experiment's goal is calculation of efficiency for each energy conversion step as well as the overall efficiency of the system.

The high school teacher conducting the course observed that students drew upon their prior knowledge (rotational motion, conservation of energy, electricity, and thermodynamics) to develop an understanding, discuss data collection and analysis approaches, and perform an engaging hands-on experiment. The analysis, however, required instructor guidance; both to process the data and to set up quantitative solutions. Moreover, from introduction to completion, the experiment consumed nearly four full 48-minute class sessions – too long for a practical and viable high school lab experiment. When adapting college-level engineering experiments for high school, it is recommended that multi-step, multi-component activities be decomposed into independent stand-alone constituent pieces. These shorter freestanding components should be designed to fit both the time limitations and the student cognitive load capacity of high school.

Keywords

Efficiency, Teaching Laboratory, Energy Engineering Laboratory Module, EELM, High School

Introduction

American students and the public are dangerously unfamiliar with Energy Sciences. According to DeWaters and Powers [1] and to Condoor [2] this ignorance is endemic. Therefore, it is prudent to increase energy-focused education in our colleges and K-12 schools. To address this need, an engineering education pedagogy called the Energy Engineering Laboratory Module (EELM™) was conceived and deployed at the college level. EELM™ pedagogy posits that energy is a topic ubiquitous to all STEM fields, and therefore energy-focused hands-on laboratory and training experiences can be developed for ubiquitous and seamless insertion into any STEM course at any level.

While EELM™ pedagogy has been successfully demonstrated numerous times at the college level, this paper reports its first high school deployment. The described experimental activity was intended for use in a college-level introductory thermodynamics course, but it was implemented without modification in an Advanced Placement (AP) Physics 2 high school class to determine viability for a secondary education audience. It turns out instructors cannot simply pluck a successful energy-focused experiment from one learning environment and plop it into another without considering and planning for the new context. This experience indicates need to modify the original assumptions underpinning EELM™ pedagogy. When porting an activity between any disparate educational environments (e.g., college to high school), the EELM™ activity design phase must include 1) understanding of the learning environment in which the activity will be deployed and 2) understanding the needs of the instructor using the activity in his/her class.

Background

Laboratory experiences are essential for successful Science, Technology, Engineering, and Mathematics (STEM) education both at the undergraduate college level and in K-12 schools. Blosser summarizes the history of STEM laboratories as education tools starting from the 19th Century when "laboratory instruction was considered essential because it provided training in observation, supplied detailed information, and aroused pupils' interest" [3]. This philosophy is still true in the 21st Century with numerous reviews and studies (more than can be cited practically here) confirming that laboratories are indeed essential for student learning in the STEM fields to promote development of 1) scientific literacy; 2) reasoning skill sets; and ability for 3) observation, 4) measurement, 5) communication, 6) classification, 7) inference, and 8) prediction [4,5].

Through its evolution over ten years, EELM™ has been used successfully at the undergraduate college level to introduce Energy Sciences across a wide variety of disciplines both with obvious and non-obvious connections to energy. Activities implemented include the following: 1) development of inexpensive audit kits for the built environment [6,7], 2) characterizing Tesla turbine performance [8-10], 3) creating simple biomass gasifiers [11], 4) studying two-phase flow isothermally expanding through a propeller turbine [12,13], 5) measuring water vapor diffusion through layered fabrics [14,15], 6) determining causes underpinning outdoor wireless mesh network hub failure [16,17], 7) evaluating solar concentrating photovoltaic and thermoelectric power system [18,19], 8) designing automatic drug dispensers and movable residential walls to facilitate seniors "aging in place" [20], and 9) constructing educational aquaponics systems for elementary school classrooms [21]. Numerous other engineering education researchers and practitioners (who were perhaps not aware of a formalized EELM™ pedagogy) have employed comparable approaches and techniques to create similar energy-focused teaching and learning activities at a variety of educational levels [22-27]. In fact, Nordeine et al showed that successful project-based energy education can be achieved even at the middle school level with appropriately designed learning experiments [28].

Following the underlying pedagogy narrative of New Learning [29], EELM™ laboratories are hands-on, accessible, and student-centered. They are also economical and "turn-key". The hardware must be affordable for an institution with limited resources and be buildable and operable by a handy course instructor or technician without situated knowledge or access to specialized tools and equipment. Table 1 summarizes the attributes of EELM™ instructional activities.

Table 1: Attributes of EELM™ instructional activities

#	**EELM™ Attribute**
1	Elucidates an important Energy Sciences principle or phenomenon
2	Easy and quick for the educator to set up, operate, and take down
3	Easily understood and operated by the learner
4	Plug-and-play, turn-key, highly reliable and trouble-free when deployed
5	Not reliant upon propriety or open-source hardware/software undergoing perpetual updates
6	Provides topics connected to the principle curriculum of the course where it is deployed
7	Highly supported through written curricula, online resources, and step-by-step procedures
8	Includes training modules for specialized instrumentation and/or complex processes
9	Promotes team collaboration but with defined roles compelling all learners to contribute
10	Users enjoy hands-on interactions with the phenomena being studied (users can modulate an independent variable to induce observable changes in a dependent variable)
11	Facilitates open-ended, inquiry-based learning and requires problem solving
12	Affordable for institutions with limited resources
13	Safe to use and observe in a modestly equipped classroom or lab environment
14	All activities can be completed in the time allotted for the laboratory/classroom session
15	Places the learner at the center of the educational process, facilitating their maturation into a peer group expert

Theoretical Modeling

The EELM™ energy conversion experiment, shown schematically in Figure 1, was deployed for this study in the high school AP Physics 2 class at Oak Hall School. Called the "Exchanging & Converting Energy Laboratory (ExCEL), the experiment includes four measurable processes that transform energy from one form to another, incur losses, and have associated efficiencies:

1) a burning candle,
2) a thermoelectric heat engine,
3) a DC motor, and
4) a lifting winch.

The goal of the experiment communicated to the students is to determine the efficiency of each of the four energy conversion processes and find the overall energy conversion efficiency of the whole experiment. The following brief analysis demonstrates what instructors expect learners to discover about each process as they work through the experiment.

Burning Candle: The chemical energy stored in candle wax is converted to thermal energy by combustion. The resulting efficiency expression is

$$\eta_{candle} = \frac{\dot{Q}_{TEG}}{\dot{m}_{wax}E'''_{wax}} \tag{1}$$

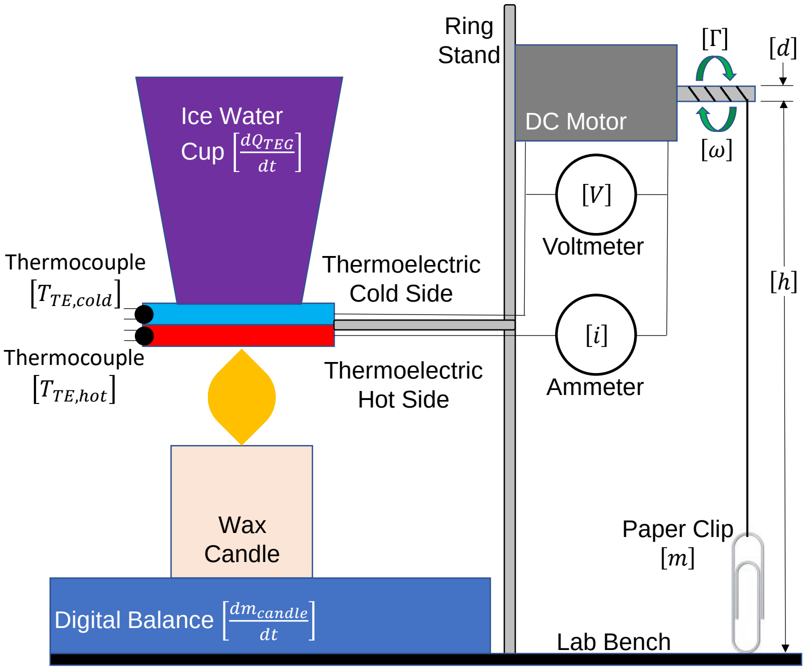

Figure 1: A schematic of the Exchanging & Converting Energy Laboratory (ExCEL) shows the various components and processes underpinning its operation.

where $\dot{Q}_{TEG}$ is the thermal energy passing through the thermoelectric generator, E'''_{wax} is the energy density of candle wax (43 kJ/g) [30], and $\dot{m}_{wax}$ is the rate of wax consumption by the burning candle, which is logged during the experiment by placing the burning candle on a digital balance.

Thermoelectric Heat Engine: A thermoelectric (TE) generator, which is a Peltier cooler run in reverse, converts thermal energy passing through the TE generator, $\dot{Q}_{TEG}$, to electrical energy. The resulting efficiency expression is

$$\eta_{TEG} = \frac{\dot{W}_{electric}}{\dot{Q}_{TEG}} = \frac{iV}{\dot{Q}_{TEG}} \tag{2}$$

where $\dot{W}_{electric}$ is the TE's electrical power output (the product of measured current, i, and voltage, V). Since the TE generator is a solid-state heat engine, this efficiency must be less than the Carnot efficiency based on the TE's measured hot-side and cold-side temperatures.

DC Motor: Electrical power from the TE generator, $\dot{W}_{electric}$, is converted to mechanical power, $\dot{W}_{mechanical}$, by the DC motor. The resulting efficiency expression is

$$\eta_{motor} = \frac{\dot{W}_{mechanical}}{\dot{W}_{electric}} = \frac{\Gamma\omega}{iV} \tag{3}$$

where i is current V is voltage coming from the TE, Γ is the motor's torque, and ω is the motor's rate of rotation.

Lifting Winch: The mass of a paperclip, m, stores potential energy, $PE_{paperclip}$, as it is lifted to a height, h, above the laboratory floor by the DC motor. In addition to the potential energy imparted to the paperclip by the lifting torque of the motor, the motor also induces kinetic energy, $KE_{paperclip}$, by accelerating the paperclip from rest on the lab floor. Thus, the resulting efficiency expression is

$$\eta_{lift} = \frac{PE_{paperclip}}{(\dot{W}_{mechanical})\Delta t + KE_{paperclip}} = \frac{\text{mgh}}{(\Gamma\omega)\Delta t + \frac{mV^2}{2}} \quad (4)$$

where $\dot{W}_{mechanical}$ is the mechanical power of the DC motor arising from the product of torque, $(\Gamma\omega)$, and rotation rate ω.

Experimental Setup

Figure 2 shows the physical set-up of the experiment in the Upper School Physics Laboratory Classroom at Oak Hall School.

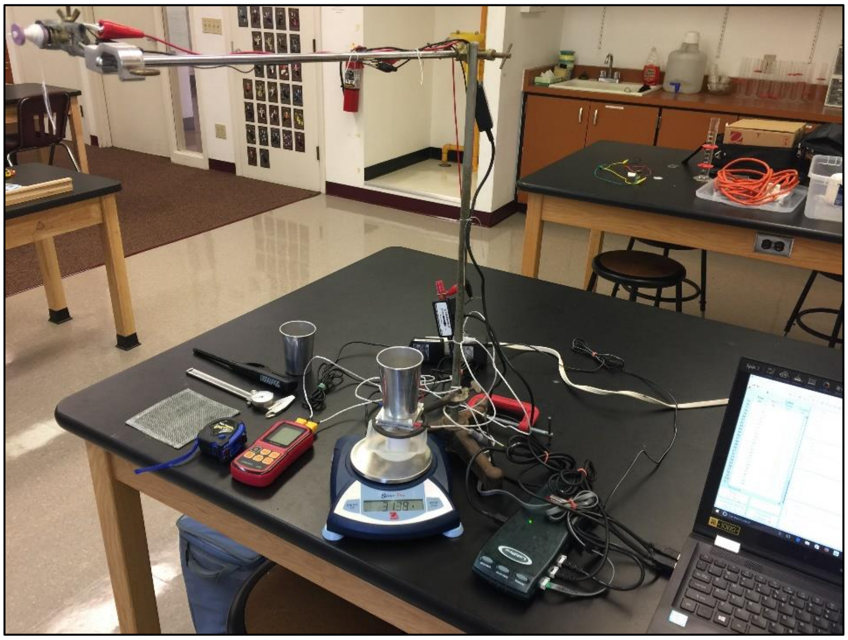

Figure 2: The Exchanging & Converting Energy Laboratory (ExCEL) shown set up on a bench in an AP Physics classroom.

Real-time data acquisition is accomplished using Logger Pro® 3 software from Vernier, running on a laptop PC. A Vernier voltage probe (Part 30V-BTA) and a current probe (Part DCP-BTA) connected to a legacy LabPro™ data acquisition unit read motor power input. A Vernier surface temperature sensor (Part STS-BTA) left hanging in the lab near the experiment reads ambient temperature. The digital balance, an Ohaus Scout Pro SP-602, feeds data directly to the computer via USB connection. K-Type thermocouples (Uxcell Model# TRTAXCEEGF833) affixed to the TE's hot and cold sides using wire spades read into a Leaton® digital dual-channel thermocouple meter. The thermoelectric generator is a Yosoo 40 mm X 40 mm high-temperature Peltier generation element. The lab stand, alligator clip wires, and other incidental components were borrowed from the physics laboratory.

To protect the TE generator from directly contacting the candle flame as well as from physical damage, the component was sandwiched between two 1/8-inch-thick aluminum plates with holes drilled in all four corners, so they could be clamped together (Figure 3 - Top). To reduce contact resistance, Halnziye HY910 white thermal glue was used to adhere the TE to the metal plates. Nylon screws then held the aluminum plates together, clamping them onto the TE generator. The screws were arranged to seat perfectly within a chemistry ring stand flask holder (Figure 3 – Bottom). Nylon was selected for the screws instead of metal to reduce undesirable thermal leakage between the plates and from the plates to the ring stand.

The DC motor was suspended off the lab bench and out over the lab floor using a lab stand elbow joint. Students determined the height from the floor to the center of the motor spindle with a tape measure, and they measured the diameter of the motor spindle with a dial caliper.

Heat flux through the TE generator was measured indirectly by monitoring the melting of ice placed in a metallic cup atop the generator's cold side. Two identical cups were weighed on the Ohaus Scout Pro SP-602 balance, filled with ice, and reweighed. The remaining cup volume was filled with tap water, and the cups were reweighed again. Now the mass of each cup, their initial charge of ice, and charge of liquid water was known. One cup remained on the lab bench, representing the ice melt rate due to ambient conditions. The other cup was placed on the generator's cold side to measure the melting rate owing to ambient conditions combined with heat flux through the TE generator. At the experiment's conclusion, the cups' contents were poured through a strainer and the mass of solid ice remaining was measured. This weight information was combined with ice's latent heat of melting to estimate $\dot{Q}_{TEG}$.

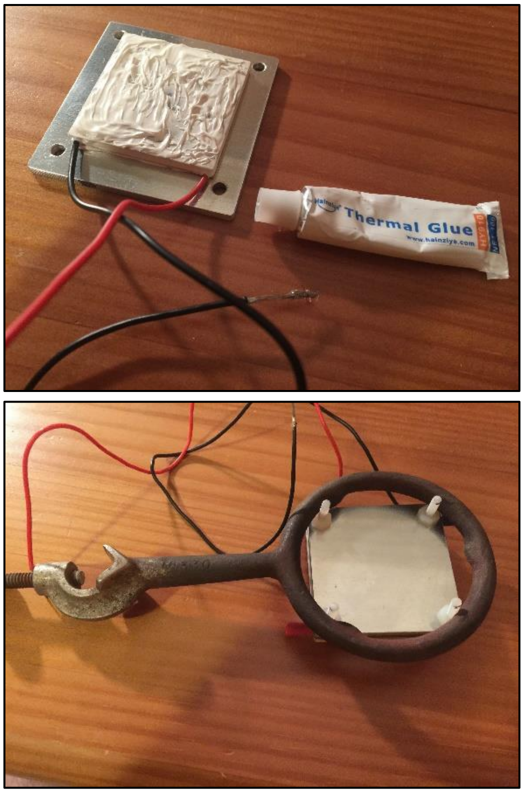

Figure 3: The thermoelectric generator module in construction. (Top) Thermal glue adheres the aluminum plates to the generator while simultaneously reducing contact resistance. (Bottom) Nylon screws clamp the plates onto the generator while seating in a ring stand.

Four AP Physics 2 students conducted the experiment, as shown in Figure 4, observed and aided when needed by the course instructor (L. M. Flewellen) and the experiment's creator (M. J. Traum). Before taking measurements, the students were given a brief review of the underlying concepts, and the procedure of steps was explained. Students performed all the measurements while the instructors started and stopped the data acquisition system and reset the apparatus between experiments.

Figure 4: AP Physics 2 students conduct the experiment under instructor supervision.

To obtain a meaningful number of data points from which statistical results could be drawn, the lifting experiment was repeated 12 times. Three students used cell phone stopwatches to manually record the time required to lift the paperclip from the ground up to the motor spindle. The fourth student recorded the total time the candle was burning over the 12 experimental runs. Previous tests of the candle alone indicated that once burning in steady state the candle's wax consumption is a linear function of time (Figure 5). So, although the candle's change in mass was recorded with time, only its initial mass, final mass, the elapsed burn time, and the energy density of wax was needed to determine the rate of chemical-to-thermal energy conversion.

After weighing on the Ohaus Scout Pro SP-602 balance to determine initial mass, the candle was lit and allowed to burn for about a minute until the flame steadied. The candle was then slid under the hot side of the TE generator. The thermocouples reading TE hot side and cold side temperatures were monitored until their values stabilized to steady state. Once this condition was met, lifting experiments were initiated by manually closing the circuit between the TE generator and the DC motor. Once the paperclip reached its final elevation, the motor was disconnected, and the student-measured lift times were manually recorded. To reset the experiment, the line winching up the paperclip was unspooled from the DC motor's spindle by hand, returning the paper clip to the ground.

Results

Table 2 summarizes the component efficiency results as well as the energy conversion efficiency for the entire system obtained by inputting collected experimental values into Equations (1) – (4) outlined in the Theory section.

Table 2: Calculated ExCEL total system and component efficiencies.

Component	Efficiency
η_{candle}	18.85%
$\eta_{thermoelectric}$	1.85%
η_{motor}	7.01%
$\eta_{lifting}$	96.98%
η_{total}	0.02%

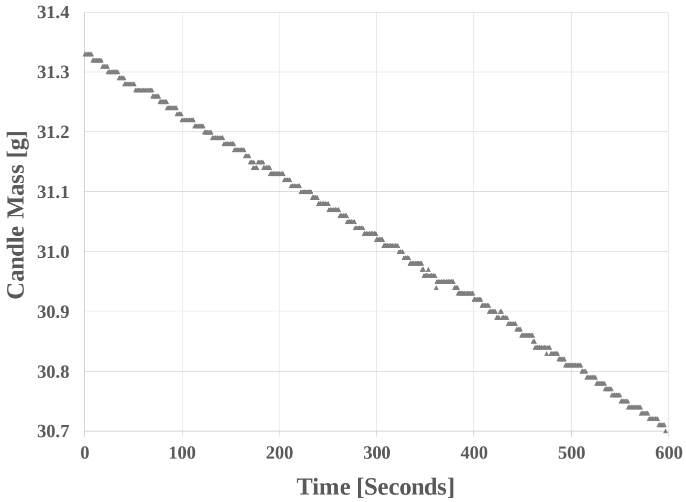

Figure 5: Burning candle mass versus time shows mass consumption rate to produce energy is linear.

Once in steady state, the candle released 47.87 watts of thermal power, and of that heat, 9.02 watts traversed through the thermoelectric generator to be captured by the melting ice water in the cup placed on the generator's cold side. During the experiment, the average thermoelectric hot side temperature was 337.55 K, the cold side was 309.85 K, and the room remained at 296.91 K. The resulting generator Carnot efficiency was 8.21%, which (as expected) was greater than the measured efficiency of this component at 1.85%.

During experimental lifts, the DC motor rotated at an average rate of 55.32 revolutions-per-second (347.61 radians-per-second) pulling the 1.26-gram paperclip 1.462 meters above the ground in an average time of 1.55 seconds, which corresponds to an average vertical lift speed of 0.945 m/s. The resulting calculated motor efficiency, 7.01%, was on par with values of approximately 10% obtained previously when using these motors in unrelated experiments. While small, inexpensive, brushed DC motors on this size scale typically have peak efficiencies around 50% [31], the DC motor used in this experiment was quite old and of marginal quality. So, below average performance was expected.

Student Engagement

In this initial high-school-level deployment, the ExCEL experiment was performed by senior students enrolled in AP Physics 2, the most advanced science class offered at Oak Hall School. These students were able to see in action through this hands-on experiment topics from AP Physics 2 (i.e., Thermodynamics) as well as topics from their prior introductory physics courses (i.e., rotational motion, conservation of energy, and electricity). As the inquiry-based AP course requirements stipulate, the students were subsequently tasked with applying this knowledge in a variety of manners, interweaving the various units in unique and engaging ways. With some guidance, the students developed an understanding of the ExCEL setup, discussed ways in which they could collect data to achieve the desired results, and performed the experiment accordingly. The students were engaged throughout the lab and even suggested some alternate methods of data analysis which would yield similar results.

For example, the students realized that $\dot{Q}_{TEG}$ could be calculated directly without need to perform the complex ice water cup weighing steps if the thermal resistance across the TE, $\mathcal{R}$, was known. Since the TE generator's hot- and cold-end temperatures ($T_{TEG,hot}$ and $T_{TEG,cold}$ respectively) were measured during the experiment, 1-dimenssional conduction would yield

$$\dot{Q}_{TEG} = \frac{(T_{TEG,hot} - T_{TEG,cold})}{\mathcal{R}} \tag{5}$$

The thermal conductivity of Bismuth telluride, the TE material making up the generator, is 1.2 W/m-K [32]. Using TE and aluminum plate dimensions measured by caliper, the conductive heat transfer resistance presented is $\mathcal{R} = 2.063$ K-m^2/W assuming a 1-dimesional resistor heat transfer model. For the measured temperature difference, the students' suggested approach gives $\dot{Q}_{TEG} = 13.4$ watts, which is suprirzingly close to the 9.02 watts measured via melting ice.

The course instructor (L. M. Flewellen) indicated that the most rewarding part of this experiment for her was watching the students hone their critical thinking skills and develop questions which demonstrated an advanced understanding of the topics at hand. The students were eager to discuss the experiment at length, stating that the interactive components were incredibly useful in furthering their conceptual mastery of the subject, a vital component of the AP exam.

Discussion

Although porting the ExCEL experiment from college to high school appeared successful with respect to student understanding, learning, and engagement, there were two elements of the exercise that did not transition smoothly to the high school environment.

First was timing. The ExCEL experiment was originally designed for a college thermodynamics laboratory course with 2 to 3 uninterrupted hours devoted to students performing a single experiment. Typical high school periods are between 45 and 50 minutes (48 minutes at Oak Hall), and do not therefore provide enough time to run the entire lab from start to finish. Making matters worse, two of the class sessions in which the experiment ran were truncated – one due to a fire drill and the second due to a modified bell schedule to accommodate a school assembly. To accommodate four short periods instead of one long one, the activity was broken into four pieces 1) lecture-based review of concepts, 2) introduction of the apparatus and its components, 3) data collection, and 4) data analysis. The drawback of fragmenting the lab is that students endured two full class days of passive learning before enjoying the hands-on experience of data collection and the activity lacked its original intended continuity.

Second, the resulting data set generated by the data acquisition system was large, complex, and nuanced; requiring one of the instructors (M. J. Traum) to invest a few hours reducing the data to meaningful results that could be analyzed by students. The two key difficulties were 1) sifting through all the null data to find the useful results and 2) deciding which voltage and current values among a varying set of values represented the electric power imparted to the DC motor during lifting. Attempting to make these values easy to spot in the data stream, the instructor pressed down on the balance weighing the candle just before connecting the motor to generate an easy-to-identify data blip at the onset of each lift. However, power data were collected when the paperclip was still on the ground (i.e., before the motor spooled up enough line to lift it), during the lift, and after the paperclip reached the motor spindle's elevation. Power data collected only during the lifting process were needed, and it was judged that high school students lacked the data analysis experience to identify the subtle differences between valid and invalid data. At the college level, students are expected to perform this data processing step to reduce data to useful form, but in high school this task would likely fall to the teacher, imposing an extra unwanted time burden and penalty for deploying this experiment.

A third issue, this one technical, was discovered while processing the experimental data: the candle did not maintain constant temperatures across the thermoelectric generator with respect to time over the whole experiment. While the burn rate was constant, the candle physically melted down during the experiment causing the flame itself to move farther away from the thermoelectric generator resulting in less heat being absorbed. While only significantly impacting the last two runs this time, this problem must be solved for future deployments. Two solutions are being considered: 1) Oil-fired tealight candles whose wicks draw fuel up to the flame and 2) methanol gel "canned heat" chafing cans, which are designed to deliver constant heat during their operation.

To mitigate the time and data complexity issues for future ExCEL deployment in high school labs, it is recommended that the exercise's multi-step, multi-component activities be decomposed into independent stand-alone constituent pieces. These shorter freestanding components should be designed to fit both the time limitations and the student cognitive load capacity of high school. Breaking ExCEL up into the following four 40-miunte lab activities is recommended.

1) Candle thermal energy production rate:
The mass of the candle is monitored as it burns, heating a TE substance which is cooled on the opposing side by an ice-water cup. The generator is not electrically connected. So, it provides no

power and only serves as an insulation layer. In this experiment, students compare the ice melt rate method to the thermal conductivity method to measure thermal power flux through the generator. The students also compare the amount of energy released by the candle to the amount conducted through the generator. This experiment prepares students to understand and visualize how heat conducts through the thermoelectric system in subsequent experiments.

2) Thermoelectric generator as a heat engine:
In this experiment, the candle is replaced on the TE hot side by an electric Kapton film resistive heater, and the ice cup is replaced on the cold side by a heat sink and an electrically-driven fan. The TE generator is connected to a variable resistor in this experiment, and its power output (Vi) is monitored. The thermoelectric's hot side and cold side temperatures are also monitored. Students adjust the power flowing into the Kapton heater to change the temperature gradient across the thermoelectric generator. They then measure the generator's power output and adjust the resistive load to find the Maximum Power Point for a given heater setting. Students then calculate the thermoelectric generator's efficiency for the variety of heater settings they explored and determine whether it behaves like a heat engine (i.e., higher temperature gradient corresponding to higher efficiency). The goal of this experiment is to introduce thermodynamic heat engine efficiency concepts while allowing the students to explore the interplay between independent and dependent variables.

3) Thermoelectric powered DC motor: Using the heater-thermoelectric system as a power source, a DC motor lifts a small mass from the floor to the lab bench. Without worrying about conduction, rates of disappearance of candle wax or ice, or temperatures across the thermoelectric students considers electrical work ($Vi\Delta t$) output from the generator / input to the motor versus mechanical work output by the motor / input to the lifted mass (mgh) to determine the motor's efficiency. The goal of this experiment is for students to consider energy loss mechanisms in the system to better understand the concept of efficiency.

4) Battery powered DC motor: Instead of a thermoelectric generator, a dry cell battery in series with a variable resistor drives the DC motor to lift the same small mass. Instead of controlling the power delivered to the motor indirectly by adjusting a heater, here students control it directly by adjusting the resistor tied to the battery. While resulting in the same analysis as the thermoelectric power DC motor lab, this exercise is framed as an open-ended, inquiry-based experiment. Students are challenged to think about differences between the thermoelectric and the battery circuit and explain the advantages and disadvantages of each power source. The students are also encouraged to render suggestions as to how to improve the procedures of all four experiments in this module.

Once students have successfully completed analysis of these four sub-systems and developed experience working with the various components, the instructor may then elect to present the class with the fully integrated ExCEL apparatus to perform stepwise energy conversion and total system efficiency analyses as intended with the original college-level experiment. This longer-form laboratory is best-suited for high schools with extended block periods set up for longer classes once per week. The instructor could also use the complexity of data resulting from the complete ExCEL experiment as a teaching opportunity, collaborating with students in real time in-class as a group to process and evaluate data. Certainly, the decision whether to introduce these more advanced activities to a high school physics class should be at the teacher's discretion.

Conclusion

The ExCEL teaching laboratory experiment was described. This system demonstrates multiple energy conversions with capability to measure input/output at each step. The experiment was intended for college-level use but was implemented without modification in a high school Advanced Placement (AP) Physics 2 class. This instance represents the first deployment of a teaching experiment designed using the EELM™ approach in a high school.

The outcome of the experiment is to lift a small mass from the lab floor, imparting to it potential energy. However, to perform the lifting, the experiment contains four energy conversion processes whose efficiencies are quantitatively measured. A candle converts chemical energy to captured thermal energy with an efficiency of 18.85%. A TE generator converts captured thermal energy to electrical energy with an efficiency of 1.85%. A DC motor converts electrical energy to mechanical energy with an efficiency of 7.01%. Finally, a winch converts mechanical energy to potential energy with an efficiency of 96.98%. The overall energy conversion efficiency of the system across all four steps is 0.02%.

AP Physics 2 high school students running this experiment were observed to be engaged, to hone their critical thinking skills, to draw upon material learned in previous courses, and to develop advanced understanding of the topics presented. The students even suggested a technique to estimate heat absorbed into the thermoelectric generator that the experiment's creator had not thought of; the approach was verified to be correct. In this respect, the ExCEL experiment was successfully deployed in a high school classroom and met its goal of furthering students' Physics conceptual mastery.

The experiment, however, was not properly adapted to the limited time blocks of a high school schedule and had to be broken up and delivered across four classroom meetings causing the experience to lack the continuity it would have had in the 2- or 3-hour college laboratory setting it was meant for. Moreover, the data analysis phase was deemed too time consuming, complex, and nuanced to be manageable by students. So, an instructor had to invest several hours reducing the raw data to make it usable. This imposition on instructor time to run ExCEL makes this experiment prohibitive it its current form for use in high schools. This experience indicates need to modify the original assumptions underpinning EELM™ pedagogy. When porting an activity between any disparate educational environments (e.g., college to high school), the EELM™ activity design phase must include 1) understanding of the learning environment in which the activity will be deployed and 2) understanding the needs of the instructor using the activity in his/her class.

For future deployment in high schools, it is recommended that the ExCEL laboratory be broken into four shorter and simpler exercises (described in this paper) that can each be completed within the time constraints of a 45-minute high school classroom meeting and do not impose cumbersome backend data analysis requirements on the instructor. At the teacher's discretion if time permits, once the class is comfortable with the four simpler exercises, the original integrated ExCEL experiment could be used as a capstone exercise to the lab sequence.

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