A Sub-Orbital Experimental Payload for Engaging Undergraduate Engineering Students in Interdisciplinary Research

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***Abstract*—By participating in NASA's Undergraduate Student Instrumentation Project (USIP), faculty members from physics and electrical and computer engineering (ECE) mentored 21 students in extracurricular undergraduate research ranging from freshman through seniors, predominantly from the ECE department, but also from other departments in science and engineering.**

In this paper, we present technical details to complete an experimental payload for sub-orbital exploration under NASA's USIP as well as analysis of post-flight survey results for its effect on student learning experience. The USIP program was created by NASA to engage and educate interdisciplinary teams of undergraduate students by providing student-designed payloads access to sub-orbital vehicles. Undergraduates take primary responsibility for all aspects of the project, gaining valuable project management experience; preparing for technical reviews; finalizing project design; and completing payload construction, testing, and integration to ensure a successful flight.

A post-flight survey was conducted to assess student learning outcomes and demonstrated that students found participation in USIP to be a valuable use of their time that increased their interest in pursuing a career in science, technology, engineering and/or mathematics. The project also provided an opportunity for students to further the learning objectives that are typically assessed in the a-k student outcomes required for ABET accreditation.

Keywords—undergraduate research, interdisciplinary research, ABET student outcomes, high-altitude ballooning, near-space exploration

I. Introduction

Traditionally, engineering students engage in a capstone senior design activity that allows them to apply knowledge, skills and abilities learned throughout the curriculum to a real world problem. However, undergraduate research provides a vehicle for students from all stages of the engineering curriculum, including freshman, to begin developing these skills much earlier in their academic career. Additionally, participation in undergraduate research has been shown to increase enrollment, retention and engagement [1].

Furthermore, interdisciplinary research provides an opportunity to develop communication skills for interactions with individuals outside the field of engineering, a skill that is increasingly important in the modern global economy. For example, the National Academy of Engineering recommends, "Undergraduate students should seek out interdisciplinary experiences, such as courses at the interfaces of traditional disciplines that address basic research problems, interdisciplinary courses that address societal problems, and research experiences that span more than one traditional discipline" [2].

Gannon University's Electrical and Computer Engineering (ECE) program, in conjunction with the physics department, has established an active high-altitude scientific ballooning program to encourage interdisciplinary undergraduate research [3][4][5][6]. During the 2013-14 and 2012-2015 academic years, a total of 21 undergraduate students from Gannon University, 16 engineering majors and five outside of engineering, participated in a project to build a cosmic-ray detector, Gannon University's Cosmic Ray Calorimeter (GU-CRC). The GU-CRC payload was designed to detect and measure the energy and charge of primary cosmic rays in the energy range of 1-100 GeV (the electron volt – eV – is a standard unit of energy used in high-energy physics and has a value of 1.60×10^{-19} J) with the purpose of measuring the ratio of protons to helium as a function of energy at balloon float altitude. The project was initially funded through a NASA Undergraduate Student Instrumentation Project (USIP) grant and flew aboard a balloon provided by WorldView Enterprises in March 2015. The payload was then mechanically and electrically modified to interface with the High Altitude Student Platform (HASP) [7] for a second flight in Sept 2015. HASP is a program, funded by the Louisiana Space Grant Consortium and operated by the Louisiana State University (LSU), to launch twelve competitively-selected student payloads per year on high-altitude balloons. This second flight was not funded by the USIP program. Both flight campaigns were successful.

Details on the student learning opportunities provided by participation in the design, construction, and flight of the

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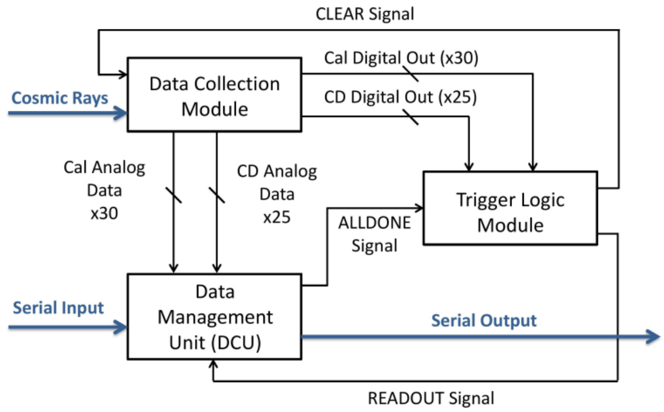

Fig. 1. Top-level representation of GU-CRC and its major functional modules.

payload will be discussed below. A student survey was used to assess the impact of the research project, and reveals that scientific ballooning provides an excellent opportunity for engaging undergraduate students in research to augment classroom learning.

II. Project Overview

A. Brief Science Background

Cosmic rays are high-energy particles of astrophysical origin. Most primary cosmic rays are composed of ionized nuclei, predominantly protons (~90%) and helium (~9%). These primary cosmic rays destructively interact with the atmosphere, causing showers of secondary particles. Studying primary cosmic rays requires placing a detector above the atmosphere, either using a high-altitude balloon or satellite. Due to cost considerations, ballooning is much more accessible to student research teams, but the CubeSat [8] format may also be an option.

Cosmic rays have been observed over a wide range of energies, but the flux decreases rapidly with increasing energy. Given the relative scarcity of high-energy events, a detector's energy range is limited by its size and flight duration. Due to the size, weight, and time restrictions for a small balloon payload, GU-CRC had a maximum energy range around 100 GeV.

B. Payload Concept

A top-level overview of the payload, including the major functional modules, can be found in Fig. 1. The data collection module consisted of a calorimeter and charge detector, which will be discussed separately below. Our students, in close collaboration with the faculty advisors, were responsible for designing, testing, and integrating all these modules to create a functional detector.

1) Calorimeter: The calorimeter consisted of six tungsten absorber layers above six layers of thallium-doped cesium iodide CsI(TI) scintillating crystals. Scintillating materials emit light proportional to the energy deposited by transiting charged particles. The absorber layers created a shower of secondary particles that were detected by the scintillator layers, while the scintillator layers were alternated between the x and y-directions to facilitate determination of the initial trajectory of the incident particle, which is necessary to properly interpret the data.

The scintillator was read out using silicone photomultipliers (SiPMs) [9]. These devices converted the light generated inside the scintillator into a small electric current. Light yield was maximized by wrapping the scintillator in a reflective material (Teflon), then covering it with black electrical tape to prevent outside light from entering.

Reading out the calorimeter gave ECE students a concrete problem to solve using the circuit design skills learned in the classroom. They designed custom electronics to readout the SiPM output and integrate it, as this integral is proportional to the energy deposited inside the scintillator. The integrator analog output was then read out by an ADC in the Data Management Unit (DMU) and recorded for post-flight analysis. A comparator on the integrator output was used to create a digital input to the Trigger Logic Unit (TLU), which determined whether to readout or clear each event.

As there were 30 SiPMs in the calorimeter, the circuit design needed to be implemented onto a printed circuit board (PCB) to conserve space. This PCB then required assembly and testing in the lab. At Gannon, current ECE courses do not provide students with the opportunity to design a circuit, lay it out on a PCB, and then fabricate and test it themselves. Students seemed to find producing a PCB to be extremely rewarding. The Eagle board layout of a single integrator board containing five integrator channels is shown in Fig. 2.

2) Charge Detector: The Charge Detector (CD) was composed of BC-444G plastic scintillator [10] also read out using SiPMs. The amount of energy deposited in the scintillator, and thus the amount of light produced, is proportional to Z^2, where Z is the elemental particle charge. Some secondary particles from the calorimeter shower will travel upward, redepositing energy inside the CD and interfering with the charge measurement. A segmented CD

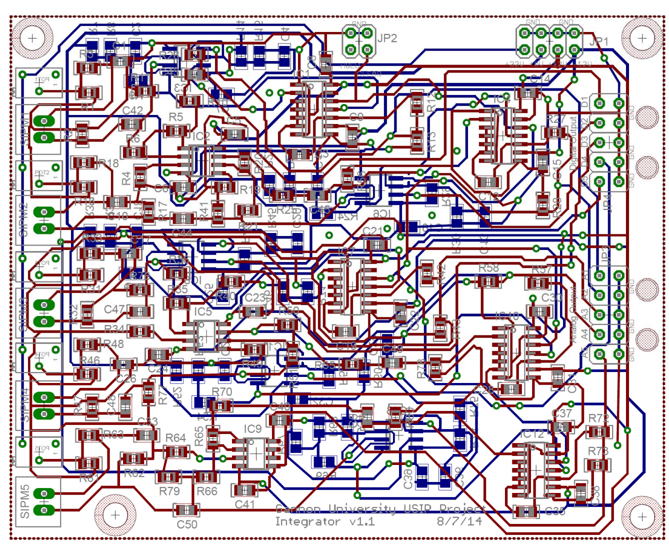

Fig. 2. Student designed PCB layout of integrator board containing five SiPM readout channels.

was used to minimize the impact of this “backsplash” by arranging the plastic scintillator in a 5×5 array above the calorimeter.

Students designed custom electronics to readout the 25 CD SiPMs as well. The CD SiPM outputs were input to custom-designed peak detector circuits. Peak detectors were used to minimize the impact of backsplash, since most albedo particles will have a charge of Z=1 and will therefore have a less significant impact on the peak of the output pulse than the area.

As with the integrator, students were responsible for all phases of circuit design, PCB layout, construction and testing of the peak detector circuit. Peak detector output also was read out by an ADC and coupled with a comparator to create a digital input to the TLU.

3) Trigger Logic Unit: The digital outputs from the integrators and peak detectors were input to the TLU to discriminate between good events, which were read out, and bad events to be discarded. Although the initial design implemented the trigger logic using an FPGA, development delays and student turnover forced a simpler design polling the digital outputs from the peak detector and integrator circuits using a Chipkit Max32 microcontroller.

In order to achieve a reasonable count rate at ground level, where the cosmic-ray flux is rather low, the trigger condition for a good event required data in at least one charge detector channel and at least one channel in two out of six calorimeter layers. After a good event, the TLU sent a signal to the Data Management Unit (DMU) to readout and store the data. The peak detectors and integrators were cleared without being stored for events that did not satisfy the trigger conditions.

Work on the TLU allowed students to gain valuable experience with digital signal processing using FPGAs and microcontrollers, as well as testing digital inputs and outputs. A custom PCB was also designed to interface with the microcontroller.

4) Data Management Unit: Students implemented the DMU with an Arduino Due microprocessor [11] and a custom PCB interface containing ADCs, a real time clock, and an SD card reader. The analog outputs of the peak detectors and integrators were input to a multiplexing ADC, which was readout by the Arduino. The microcontroller then wrote these ADC values, as well as the time from the real-time clock and temperature values from several temperature sensors, to the SD card. Data readout was initiated by a signal from the TLU.

The microcontroller was also responsible for serial communication between the payload and the ground crew. Although no commands were necessary during either flight, the microcontroller was capable of receiving commands via the serial interface. It also transmitted downlink data containing event data and system health information (operating temperature) every 30 seconds to verify proper operation of the payload.

Implementing the DMU provided an opportunity for students to gain experience with the popular Arduino language and hardware. It also required learning about several different communications protocols, including SPI, I2C, and serial.

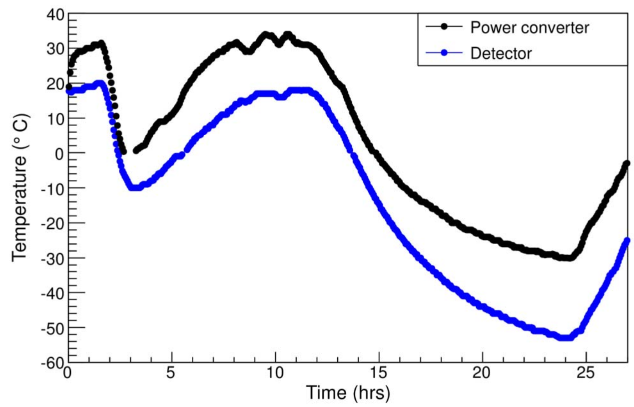

Fig. 3. Payload temperature during HASP flight.

C. Flight Results

NASA covered the launch costs as part of the USIP grant. The first flight of the GU-CRC payload was provided by aerospace company Worldview Enterprises on March 8, 2015. The balloon carried the payload to an altitude of ~32 km for ~1.7 hrs. Prior to the flight, a faculty-lead team of four students travelled to Tucson, AZ to integrate the payload with the flight provider.

The second flight, which was not covered by the USIP grant, was provided by HASP on September 9, 2015 and maintained a float altitude of ~34 km for ~23 hrs. Prior to the fight, an integration team of two students and one faculty member participated in integration and payload environmental testing at the Columbia Scientific Ballooning Facility in Palestine, TX.

Not only did student travel provide an effective recruitment tool and reward for project participation, students were able to observe first-hand the work environments of scientists and engineers.

Analysis of flight data provided an opportunity for students to gain skills in programming and data analysis. Since the second flight was longer and higher, a few selected results from this flight are presented below.

As can be seen in Fig. 3, the internal payload temperature remained between about -50°C and 30°C throughout the flight. Although some components were only rated down to -40°C, all electronics seem to have functioned properly. As expected, the temperature sensor attached to the power converter (which generates a significant amount of heat) registered a higher temperature than that attached to the detector frame.

Histograms of the energy deposited in one calorimeter integrator and one CD peak detector are given in Fig. 4. As corrections for temperature and time variation have not yet been fully implemented, these plots are from a fairly stable one hour period of the flight. Calorimeter energy deposit is given in ADC units, as the results of a currently incomplete detailed instrument simulation are required to convert to energy units. A plot of ground data just prior to launch is also included and demonstrates that significantly more energy was deposited in the calorimeter during the flight than while on the ground. This is consistent with performance expectations. To properly

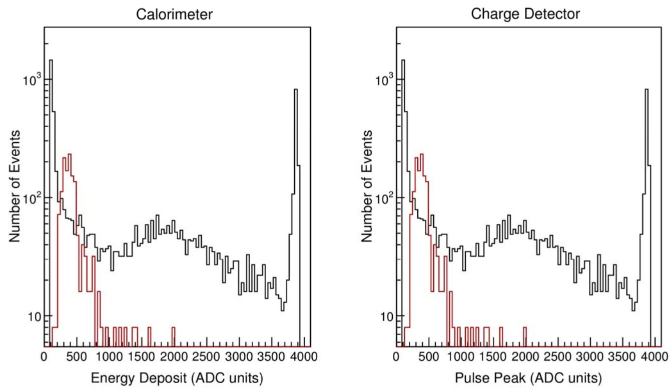

Fig. 4. Energy deposited in calorimeter (left) and CD (right) scintillators during flight (black) and prior to flight (red)

interpret the charge data, the histograms must be corrected for path length through the detector, but there are clearly more high-charge particles than were observed on the ground.

A Monte Carlo simulation of the detector has been created using the high-energy simulation toolkit Geant 4 [12]. This toolkit allows detailed simulations of particle interactions, which will be used to calibrate the detector response using ground data. Working with Geant 4 provided students the opportunity to gain experience interfacing with a complex C++ library. A calorimeter shower from this simulation is shown in Fig. 5.

D. *Project Management*

The establishment of common lab times was crucial to the overall success of the project. At the start of each semester, students submitted their class schedules and were assigned specific lab hours that overlapped other students and at least one faculty advisor. Students were required to volunteer ~5 hours each week in order to participate. Most students found the project interesting enough to volunteer without compensation, but small scholarships and paid summer hours were also effective motivators.

The formal structure of weekly lab hours proved effective

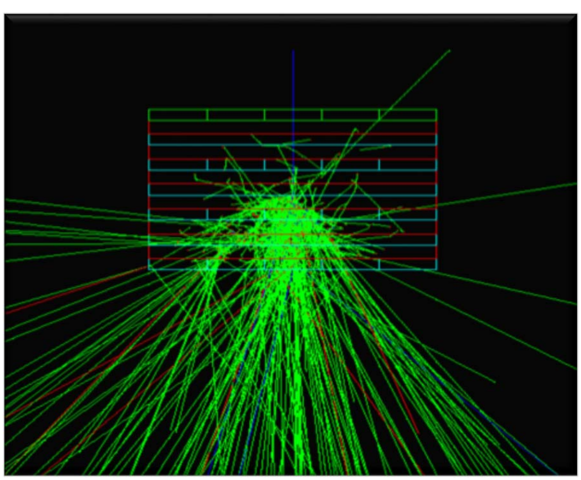

Fig. 5. Simulation of a calorimeter shower

TABLE I. NUMBER OF STUDENTS FROM EACH CLASS RANK

Academic Year	Class Rank			
	Freshmen	***Sophomore***	***Junior***	***Senior***
2013/14	2	5	2	3
2014/15	3	2	5	4

for ensuring progress toward project completion. Students had clear attendance expectations and were accountable to one another and the faculty advisors. During lab hours, faculty members worked closely with students, assigning tasks, answering questions, and motivating those who were not making progress. Monthly teleconferences and progress reports, described in more detail below, also added a layer of accountability.

Three student management positions were also created to provide project management experience and encourage students to take responsibility for project success. These positions were Team Lead/Project Manager, Engineering Lead and Science Lead. Several students were able to fill these positions throughout the life-cycle of the project.

III. Student Learning

The primary goal of GU-CRC was to excite undergraduate students about space science and engineering by giving them an opportunity to design, construct, and test a science payload while familiarizing them with the interdisciplinary research process, including project management, documentation, and external reviews.

A. *Interdisciplinary Collaboration*

Literature acknowledges that many engineering students graduate without developing the level of communication skills required to excel in the workforce [13]. As upper-level courses in both engineering and science programs tend to be insular, undergraduate research provides a unique opportunity for students to develop communications skills with people outside their major discipline.

Because the project team was composed of both engineering and science majors, and the payload was designed to collect science data, a high degree of interdisciplinary collaboration was required. The faculty mentors intentionally scheduled lab hours concurrently with science and engineering students to ensure maximum exposure to the different cultures and approaches to problem solving. Often science and engineering students were paired for a task to help and learn from one another. This arrangement seems to have been successful, as evidenced by the results of the post-project survey discussed below.

B. *Interclass collaboration*

As shown in the Table I, students from all class ranks, freshman through senior, were able to meaningfully participate in this research project. Students with more experience were given the opportunity to mentor and train the new students. This peer mentoring approach helped the experienced students reinforce their knowledge while allowing new students to quickly acquire the basic skill set needed to contribute to project completion. This mentoring relationship was formalized by creating the three management positions described previously.

New and younger students were trained in the necessary skills to complete simple tasks consistent with their background and abilities that could be completed quickly. More complex tasks were assigned as their skills and confidence increased. This approach allowed new students to contribute to completing project goals while also developing their knowledge and skills.

C. Technical Skills

Completion of specific project activities allowed students to gain proficiency in a number of technical skills. Table II links specific project activities and assignments with the technical skills developed while completing them. For the most part, the project reinforced and augmented the technical skills learned as part of the engineering curriculum. However, some useful technical skills, such as soldering and researching products from vendors' websites, are not typically included in the Gannon ECE curriculum.

D. Project Reporting and Reviews

Participation in both USIP and HASP required submission of monthly progress reports. Completion of these monthly reports allowed students to develop management skills and ensured accountability by continuously assessing progress towards monthly goals. Preparation of these reports also encouraged development of written communication skills. There were also monthly teleconferences with program sponsors to discuss the results of these reports, which fostered oral communication skills

In addition to the monthly reports, USIP program requirements mandated a preliminary design review (PDR) of the payload. Students prepared a presentation describing not only the payload and mission concept, but also identifying risks to project success and outlining project management strategy. Not only did the PDR provide students with a top-level understanding of the mission, it also helped them develop their oral presentation skills.

TABLE II. TECHNICAL SKILLS DEVELOPED DURING PROJECT

Project Activity	Technical Skills/Proficiencies Developed
Parts research and selection	• Reading datasheets/technical data to determine which parts best meet design requirements • Researching vendors to find the most cost effective option that meets design specifications
SiPM/scintillator assembly and testing	• Use of basic lab equipment (oscilloscopes, etc.)
Peak detector and integrator circuit design	• Use of basic lab equipment (oscilloscopes, etc.) • Designing a circuit to perform a function • Designing around and debugging non-ideal behavior of components (op amps, diodes, etc) • Use of Eagle PCB software, including schematic editor, custom libraries, and board layout
Assembly and testing of PCB circuits	• Surface mount soldering techniques • Use of basic lab equipment (oscilloscopes, etc.) • Circuit debugging
Monte Carlo simulation and analysis coding	• Programming in C++ and Matlab
Microcontroller I/O (digital I/O, ADC, real time clock, SD card)	• Programming in C++ and Arduino • SPI, I2C, and serial communications • Microcontroller digital I/O
Trigger logic board design and testing	• FPGA programming in VHDL • VHDL behavioral simulations • Arduino microcontroller programming
Support structure design and construction	• CAD design • Basic machine shop skills
Subsystem integration	• Use of basic lab equipment (oscilloscopes, etc.) • Programming in C++ and Arduino • System-level debugging
Payload integration with flight provider	• System-level testing, verification, and debugging • Communications debugging

E. Survey Results

Student learning outcomes were assessed using a survey that was based on a series of surveys in previous academic years that had been employed to assess the efficacy of the scientific ballooning program at Gannon [6]. All survey questions and responses are presented in Table III

Only 16 of the 21 students were contacted to participate in the survey. Some of the omitted students had graduated and we no longer had current contact information, while others had only been involved in the project for a very short time. Of the 16 who were contacted, 11 responded to the survey (three from math/science, eight from engineering).

Ten of the 11 indicated that they agreed or strongly agreed that "Participating in this project was a valuable use of my time." The same number responded that they agreed or strongly agreed that "My interest in pursuing a career in science, technology, engineering, and/or mathematics has increased." Eight out of 11 indicated that "I am more interested in pursuing a career in space science or engineering." This project has been very successful at engaging students and encouraging them to pursue science and engineering careers.

Furthermore, the students were asked specifically about the ABET "(a) through (k)" learning outcomes. The first series of questions (6a-6k – highlighted in green in the table) asked students if this project had provided an opportunity to meet these learning outcomes, while the second set of questions asked students if their participation had improved these learning outcomes (7a-7k – highlighted in violet). While there were a few negative responses, particularly relating to outcomes (h) and (i), students overwhelmingly indicated that they believed this project provided an opportunity for them to improve these outcomes. It is also noteworthy that the negative responses were all from the same student, and that student self-identified as a science/math major, not an engineer.

More informally, the faculty members observed that students had a very positive attitude toward this research project, and several of them recruited friends to join. Students also were willing to volunteer additional time on weekends as the project deadline drew near, demonstrating their outstanding level of commitment.

IV. Conclusions

The GU-CRC payload, developed with funding from a USIP grant, provided an excellent undergraduate research opportunity. Engineering and science students were able to work together to complete a complex payload design while developing interdisciplinary communication and technical skills. Furthermore, the inclusion of students from all class ranks, instead of just seniors, allowed the benefits of the senior-design capstone experience to be shared with students much earlier in the engineering curriculum. A student survey indicates that the project was successful at generating student interest in engineering while simultaneously providing opportunity to develop the ABET (a) through (k) learning outcomes. It is clear that high-altitude ballooning presents an excellent option for student research, engagement, and learning.

Acknowledgment

We are grateful to the many undergraduate students who have participated in Gannon University's high-altitude ballooning program, as well as Worldview Enterprises and the HASP team at LSU for their excellent balloon-launch support.

TABLE III. STUDENT SURVEY RESULTS

Question	# of Responses	Responses					
		Engineering			***Science and Math***		
1) Please select the option that most closely reflects your major	11	72.7%			27.3%		
		1	***2***	***3***	***4***	***5***	
2) Approximately how many semesters did you participate in (USIP). (If you worked on the project over the summer, count that as a semester.)	11	27.3%	36.4%	9.1%	9.1%	18.2%	
		Strongly Agree	***Agree***	***Neither Agree nor Disagree***	***Disagree***	***Strongly Disagree***	***N/A***
3) Participating in this project was a valuable use of my time.	11	63.6%	27.3	0.0%	9.1%	0.0%	0.0%
4) My interest in pursuing a career in science, technology, engineering, and/or mathematics has increased.	11	45.5%	45.5%	0.0%	0.0%	0.0%	9.1%
5) I am more interested in pursuing a career in space science or engineering.	11	9.1%	63.6%	9.1%	0.0%	9.1%	9.1%
6a) This project provided the opportunity to improve my ability to apply knowledge of mathematics, science, and engineering.	8	87.5%	12.5%	0.0%	0.0%	0.0%	0.0%
6b) This project provided the opportunity to improve my ability to design and conduct experiments, as well as to analyze and interpret data.	8	87.5%	0.0%	0.0%	0.0%	0.0%	12.5%
6c) This project provided the opportunity todesign a system, component, or process to meet desired needs within realistic constraints has improved.	8	50.0%	37.5%	0.0%	0.0%	0.0%	12.5%
6d) This project provided the opportunity to improve my ability to function on a multidisciplinary team.	8	62.5%	12.5%	25.0%	0.0%	0.0%	0.0%
6e) This project provided the opportunity to improve my ability to identify, formulate, and solve engineering problems.	8	62.5%	37.5%	0.0%	0.0%	0.0%	0.0%
6f) This project provided the opportunity to improve my understanding of professional and ethical responsibility.	8	37.5%	25.0%	25.0%	12.5%	0.0%	0.0%
6g) This project provided the opportunity to improve my ability to communicate effectively.	8	62.5%	12.5%	12.5%	12.5%	0.0%	0.0%
6h) This project provided the opportunity to broaden my understanding of the impact of engineering solutions in a global, economic, environmental, and societal context.	8	62.5%	25.0%	12.5%	0.0%	0.0%	0.0%
6i) This project provided the opportunity to improve my recognition of the need for, and an ability to engage in life-long learning.	8	50.0%	37.5%	0.0%	0.0%	0.0%	12.5%
6j) This project provided the opportunity to enhance my knowledge of contemporary issues.	8	50.0%	25.0%	12.5%	0.0%	0.0%	12.5%
6k) This project provided the opportunity to improve my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	8	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%
7a) My ability to apply knowledge of mathematics, science, and engineering has improved.	11	63.6%	18.2%	18.2%	0.0%	0.0%	0.0%
7b) I have improved my ability to design and conduct experiments, as well as to analyze and interpret data.	11	45.5%	45.5%	0.0%	0.0%	0.0%	9.1%
7c) My ability to design a system, component, or process to meet desired needs within realistic constraints has improved.	11	54.5%	36.4%	0.0%	0.0%	0.0%	9.1%
7d) My ability to function on a multidisciplinary team has improved.	11	45.5%	36.4%	18.2%	0.0%	0.0%	0.0%
7e) My ability to identify, formulate, and solve engineering problems has improved.	11	45.5%	45.5%	0.0%	0.0%	0.0%	9.1%
7f) My understanding of professional and ethical responsibility has improved.	11	36.4%	36.4%	9.1%	9.1%	0.0%	9.1%
7g) My ability to communicate effectively has improved.	11	54.5%	18.2%	18.2%	9.1%	0.0%	0.0%
7h) My understanding of the impact of engineering solutions in a global, economic, environmental, and societal context has broadened.	11	54.5%	27.3%	18.2%	0.0%	0.0%	0.0%
7i) I have improved my recognition of the need for, and an ability to engage in life-long learning.	11	45.5%	45.5%	9.1%	0.0%	0.0%	0.0%
7j) I have enhanced my knowledge of contemporary issues.	11	54.5%	18.2%	27.3%	0.0%	0.0%	0.0%
7k) My ability to use the techniques, skills, and modern engineering tools necessary for engineering practice has improved.	11	54.5%	45.5%	0.0%	0.0%	0.0%	0.0%

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