Educational Experiences and Lessons Learned in the Multidisciplinary Design, Fabrication, Integration and Pre-Flight Testing of Embry-Riddle High Altitude Science Engineering Rig (ERHASER) Payload Aboard NASA's WB-57 Aircraft

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Abstract

This paper describes the unique educational experiences and highlights the lessons learned during the multidisciplinary design, fabrication, integration and flight testing preparation of our prospective payload as part of the NASA's Student Opportunities in Airborne Research (SOAR) pilot program aboard the WB-57 aircraft. Our payload was comprised of several modular experiments referred as the Embry-Riddle High Altitude Science Engineering Rig (ERHASER), which was tested at about 60,000 feet during an analog suborbital trajectory over the Gulf of Mexico. One of the ERHASER's experiments was dedicated to fly an ADS-B technology kit that can enhance students' knowledge in Science Technology Engineering and Mathematics (STEM) with emphasis in aviation, and understand some of the challenges the Federal Administration Aviation (FAA) is facing with integrating new emerging era of suborbital space vehicles into the National Air Space. Understanding suborbital requirements, procedures and ADS-B performance are critical to better assess prospective point-to-point suborbital flights. This is a great opportunity for Embry-Riddle students to use the WB-57 research platform as a high-altitude performance aircraft in testing the functionality of ADS-B technologies during these analog suborbital trajectories. ERHASER's second experiment consisted of radiation environmental measurements to test its effects on *in-vitro* biological alterations. Our biological system was composed of murine T-cells primed with different cytokines and cells treated with medicinal plant supercritical extracts. The goal of this study is to investigate the radiation induced cellular damage on these murine immune cells during the WB-57 flight, and to determine the role of supercritical extracts in reversing the epigenetic changes potentially induced by exposure to radiation. These unique experiences provide guidelines that helped faculty to work with students from different disciplines to design, fabricate, integrate and conduct flight tests successfully.

Keywords

WB-57 flight, ADS-B, radiation, payload integration, biology, airborne research

Nomenclature

1U	= 10 cm x 10 cm x 10 cm
2U	= 20 cm x 10 cm x 10 cm
4U	= 20 cm x 20 cm x 10 cm
12U	= Two 4U and two 2U
ABS	= Acrylonitrile Butadiene Styrene
ADS-B	= Automatic Dependent Surveillance-Broadcast

CoA = College of Aviation
CoAS = College of Arts and Sciences
CoE = College of Engineering
COTS = Commercial Off-the-Self
CSO = Commercial Space Operations
ECLSS = Environmental Controlled Life Support System
ERAU = Embry-Riddle Aeronautical University
ERHASER = Embry- Riddle High Altitude Science and Engineering Rig
FAA = Federal Aviation Administration
GCR = Galactic Cosmic Ray
HZE = High Atomic Number (Z) and Energy
LET = Linear Energy Transfer
SOAR = Student Opportunities in Airborne Research
STEM = Science Engineering Technology and Mathematics
UTHSCSA = University Health Science Center in San Antonio
WB-57 = Weather Bomber-57 (NASA airborne research aircraft)

Introduction

This project provided a better understanding of the radiation effects in our payload experiment onboard the NASA's WB-57 (NASA927) aircraft[8]. The experiment, entitled Embry-Riddle High Altitude Science and Engineering Rig (ERHASER), took place on December 1st 2017 from Ellington Field airport in Houston, Texas. Embry-Riddle Aeronautical University was one of the five universities selected by NASA to participate in this pilot study, which was influenced in the first place by former NASA astronaut Nicole Stott. In this paper, we focused on two of the modular experiments in the ERHASER payload. The first experiment is the ADS-B technology experiment and the second one is the environmental measurements of radiation and its effects on *in-vitro* biological alterations. Both experiments were housed in two NanoLabs that were contained within two metallic boxes. Each NanoLab (4U and 2U where 1U is 10 cm x 10 cm x 10 cm) housed the biological experiment, thermal sensor, TimePix radiation sensor, eld-4S sensor, and other instruments.

The ADS-B can provide unprecedented flight-tracking data in the Gulf of Mexico area, where the payload was launched from Ellington airport. Understanding suborbital requirements, procedures, and ADS-B performance are critical to better assess prospective point-to-point suborbital flights[1] and better understand the navigation capabilities in the Gulf of Mexico where prospective spaceports are currently being built. Preliminary results of the ADS-B are provided in this paper. The second experiment can provide new data that will then be compared with other radiation models to better analyze the reactions of biological systems. The team is currently post processing the cells at University of Texas Health Science Center in San Antonio (UTHSCSA) and will reveal such findings in a future manuscript. Some preliminary results about the thermal sensor and TimePix radiation sensor will be provided in this paper. Recent studies[2] of radiation sensors, flown at altitudes near 56,700 feet and above 50 degrees latitude in both hemispheres, have recorded surges in ionization radiation — "radiation clouds". Recently, NASA studies[3] have identified several gaps associated with the risk of radiation exposure and their effects on the central nervous system. The goal of our second experiment is to characterize the biological effects of radiation near 60,000 feet on murine immune T-cells. Given that secondary particles from scattering the GCR peak near this altitude, we will be performing a phenotypic analysis of different T-cells sub-populations, investigating the effect of radiation in responsiveness to different cytokines, and assessing cells functionality. Moreover, it is well established that exposure to radiation can cause DNA damage. Therefore, we will be examining the role of the so-called supercritical extracts in reversing the epigenetic changes potentially induced by exposure to radiation.

Fabrication, Manufacturing and Integration of the Rig

Over the course of the project, several lessons were learned that covered a wide range of interests in the project development. One of the major lessons learned over the course of the experiment was knowing the loads that needed to be applied on the structure supporting the experiments. Two iterations of the structure were designed and modeled to have better understanding about the flow of stress when it was loaded with the experiments and how the G-loading would affect the structural integrity as displayed in Figure 1 and Figure 2. We refer to G-loading as the g-force that acted on each of the metal boxes, which contained the NanoLabs that housed the experiments and instrumentations, under various loads.

The structure was designed without prior knowledge of the G-loads the body would undergo, as a result, the structure went through a reinforcement phase much later in the project timeline where the original structure was enhanced by the addition of more fasteners and brackets. A decision was made during the fabrication process of using steel plates instead of aluminum plates which would increase the overall weight of the structure but that was a compromise done to ensure the rigidity of the structure when tested at different attitudes. This was highlighted during the testing process when the structure was subjected to a downwards loading of 3 Gs during which the aluminum bars showed temporary deflection (Figure 1) while the steel plates remained straight and level while the mounting brackets showed no deflection or deformations when placed on the stand-offs.

Figure 1. G-Loading test shows temporary deflection after 370 lbs. were suspended from the rig at the Structures Lab in the College of Engineering (CoE).

Also temporary deflection was observed during a G-loading of 6 Gs (Figure 2). Another crucial lesson that was learned from this experiment was to always be ahead of schedule by a minimum of a week.

An important lesson learned from this experiment and was reflected upon after completion was to design the experiment to the design requirements but not limit the design to future iteration and implementation. This was an obstacle for the team and was difficult to overcome later in the timeline of the experiment rather than correcting it earlier. Finally, keeping a high quality of work in every aspect of the project was the most important lesson learned from this project. Keeping a high standard allows for all other tasks to flow smoothly and keeps the project on a timeline to complete the project successfully.

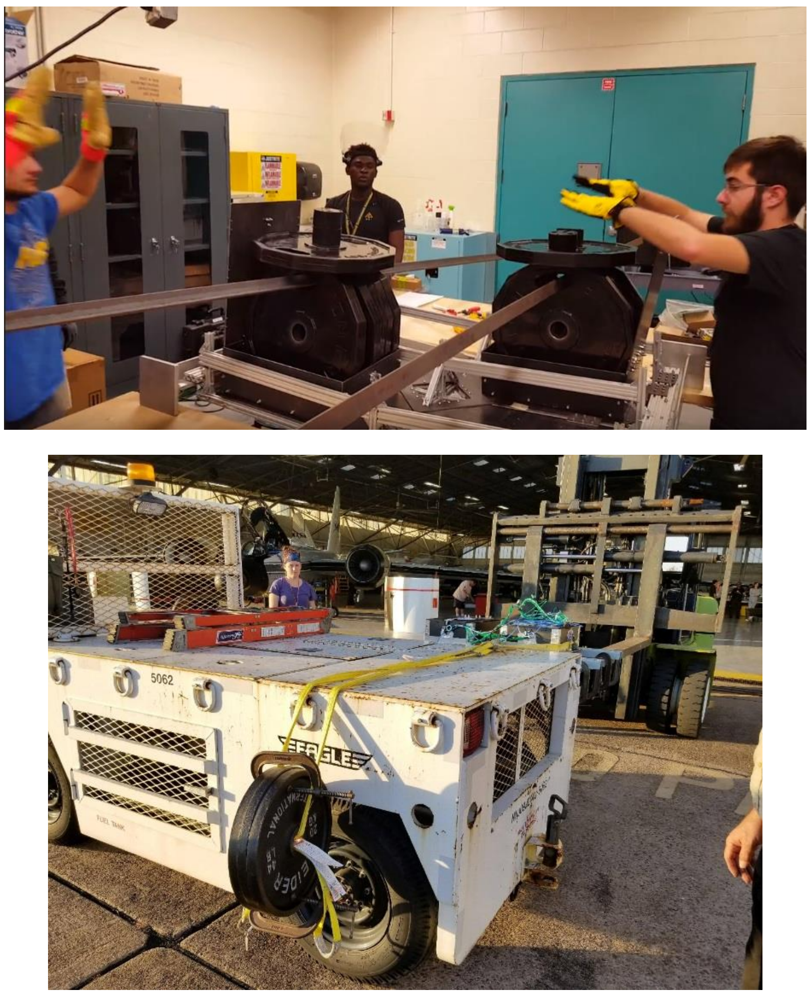

Figure 2. Top: G-Loading test shows temporary deflection after 778 lbs. were placed on top of the rig at the Structures Lab in the CoE. Bottom: Final structural G-load test at Ellington Field with AOD team.

Having the teams complete tasks ahead of the deadlines minimized confusion and provided a buffer zone for unexpected events that would negatively impact the timeline of the mission. The last and perhaps another lesson learned from this experiment, is the importance of communication between the different teams to ensure that any changes made match both the experiment and the main structure.

Design, Printing and Integration of the 12U NanoLab

Our team went through several design iterations for the NanoLab (Figure 3) before it was ready for flight. Our 12U NanoLab (two 4U NanoLab and two 2U NanoLab) was redesigned to increase its reusability from previous designs. This reusable NanoLab allows for a more flexible and reconfigurable NanoLab that can house future payloads for suborbital and orbital flights. The 12U NanoLab was designed to house an *in-vitro* biological system in the modular NanoLab. Within the NanoLab, various sensors were used to monitor the environmental conditions, such as temperature, relative humidity, accelerations and carbon dioxide. Since the operational thermal limits of these sensors have various range of temperatures, a thermal system was designed for heating and cooling these individual sensors (Figure 3).

Figure 3. Left: Operational procedures to interface instruments with electrical and thermal systems before final assembly onto the rig at the Payload and Integration Lab in the College of Aviation (CoA). Right: Final configuration of ERHASER payload right before flight at Ellington Field on December 1, 2018.

Both passive and active thermal techniques were used to fulfill the operational requirements for such sensors. The operational thermal limits for the edl-4S, and EL-21 CFR TP LCD instruments were 0 ^{o}C to 50 ^{o}C and -35 ^{o}C to 80 ^{o}C, respectively. The biggest challenge was to keep the edl-4S within the operational thermal limits from -60 ^{o}C to within a few degrees above 0 ^{o}C. For this the team used aerogel spaceloft 5 mm thick insulation that was placed inside the 12U NanoLab. Inside this 12U NanoLab, we have another smaller NanoLab to house this instrument, also isolated with aerogel, and then taped it with thermal tape. The operational thermal limit of the ADS-B device is -20 ^{o}C to 55 ^{o}C.

The modular 12U NanoLab was not only designed to first fulfill the operational requirements of our experiments but also to optimize the mass of the NanoLab and reduce the printing material and time of the print. Our NanoLab was designed to increase the flexibility of integration of the scientific experiment and sensors inside.

For this, we designed the 12U NanoLab as follows: 1) First block is a 4U section of the 12U NanoLab, 2) Second block is a symmetric 4U NanoLab, 3) Third block is a 2U NanoLab, 4) Fourth block is a repeated 2U NanoLab. The first and second blocks (science blocks) housed a single EL-21CFR-2-LCD Temperature/Relative Humidity/Dew Point sensor, and the edl-4S. These devices measured the conditions at which the T-cells, medicinal plants and supercritical extracts cells that were exposed during the 4 hours aboard the WB-57 flight. The third and fourth blocks (avionics blocks) housed the electronics, such as the Arduino, pressure sensor, thermocouples and cables to provide power to the heating pads that actively controlled the temperature inside each of the first and second blocks.
The following steps helped to reduce the cost of the ERHASER project during June-November 2018:

- *Identified and addressed science mission requirements, objectives, and NASA milestones* in the Payload and Integration class, CSO 390, with lecture notes, meetings, and presentations.
- *Constant communication* between team members: looked for innovative solutions by gathering team's feedback and suggestions, which created a new set of cross-fertilized ideas, and propelled the project forward.
- *Familiarity* with NASA documentation, such as the *WB-57 Handbook*, the Payload Data Package (*PDP*) document which was written and updated through various *status reports* on a weekly basis with NASA's mentors. Learned how to study material data sheets to ensure flight hardware was approved by NASA.
- Using Commercial Off-the-Shelf (*COTS*) helped having extensive operational complexity in the ERHASER project.
- *Small team-mentality* with the ability to change design requirements, and quickly make decisions to *increase* the *flexibility* and *reliability* of the system, and alleviate some of the student's responsibilities due to schedule conflicts.
- *Reduce operations complexity*, *payload integration procedures and risk* by increasing the modularity of our 12U NanoLab and the rig. For this, it was imperative to allow for *large margins* since even last design changes and adjustments were crucial to improve the NanoLab design functionality.
- *Reusability* of the 12U NanoLab for prospective suborbital with various commercial providers, and orbital flights.
- Total *budget* of the project hardware was under $8,000. This included the structural rig, sensors, NanoLab housing for science experiment, other accessories.

The College of Aviation (CoA) 3D Raise N2 printer has the capability of theoretically printing a 24 inches (height) by 12 inches (depth) by 12 inches (length). For the ERHASER project, we designed a 12U NanoLab. As a first step we printed a 6U (12 inches) but warping was generated in the print. Even though very specific printing tolerances were considered when executing the print, one of the sides of the 6U NanoLab warped, which led us to think that the bed did not transfer the heat uniformly or there was some issues with the printing material (ABS) when adhered to the printer bed.

The team decided to downsize it to a 4U for printing purposes in the horizontal position, yet the 3D printer produced some warping. We had several alternatives to go around it: print the 4U in the vertical position so only the 2U base of this 4U NanoLab would be on the printer bed or downsize the 4U to a 2U volume in the horizontal position and avoid further supports in some of the parts of the NanoLab. The orientation of the print mattered, especially for larger prints, so we used the height of the printer to our advantage to leverage some of the printing issues in a certain direction. Assuming our NanoLab does not require many supports, we can orient the 4U NanoLab as 20 cm height by 20 cm length by 10 cm width, which is a better printing option that placing the 4U NanoLab on the print bed as 10 cm height by 20 cm depth by 20 cm length. This desired orientation was selected in order to avoid possible warping in the depth and length directions. The print in the height direction generates slight shift layers, especially in sharp corners. The total printing time for each of the first and second blocks was near 62 hours.

It is important to mention that the print needed a raft to avoid warping. The raft was comprised of 5 layers: the two first-layers printed at 4 mm/s, an interface layer printed at 10 mm/s and two surface layers printed at 20 mm/s. The raft gap between the raft and the model was 0.2 mm, and the raft and skirt were printed with supports for over 60 degrees overhang angle. As for the 12U NanoLab, the infill was 35% with three shells (outer number of layers in wall). The resolution or layer height was specified to 0.2 mm with an extrusion width or nozzle diameter of 0.4 mm. The default printing speed was 50 mm/s but first layer speed was reduced to 5 mm/s. The first layer height was half the normal layer height, 0.1 mm. The infill pattern type is rectilinear, which provides a faster motion and less problems, although we found out that is weaker when compared to the grid model. The fan played an important role, it was off when the first layer printed but it was fully operational for the second layer. This was important to make sure the first layer was properly adhered to the raft and avoid warping. The ooze retraction speed was 25 mm/s and retraction material amount was 4 mm. Building supports to 3D print the NanoLab was crucial to obtain a clean interface with subsequent layers. We assumed 3 layers at 50% infill ratio at 25 mm/s support speed. We also moved the model 1 cm to the right of the bed (x-axis or length axis) to center the print job.

Operations and Preparation of Scientific Experiment

The 12U NanoLab was printed in various science and avionics sections: 1) One 4U left (4UL), 2) one 4U right (4UR), 3) one 2U left (2UL), 4) One 2U right (2UR), 5) left lid for 4UL, 6) right lid for 4UR, 7) left lid for 2UL, and 8) right lid for 2UR. The data logger edl-4S was placed under the 2UL lid, similarly the EL-thermal sensors was placed in the 2UR.

Our second experiment comprised of two different types of T-cells: 1) activated mature T-cells; 2) Non-activated, so called naïve T-cells. In total, there were 30 Eppendorf tubes (5.0 mL each) of such cells in the science blocks. We manipulated our mature and naïve T-cells by adding different growth factors, called cytokines, into their standard growth media. Specifically, we had 4 tubes with control (not pre-conditioned) cells, 4 tubes with cells treated with interleukin IL-2, 4 tubes with cells treated with interleukin IL-12 cytokines, and 4 tubes consisting of cells pre-conditioned with both of these interleukins for both mature and T-cells. The remainder of tubes contained cells pre-conditioned with the supercritical extract of neem leaf (*Azadirachta Indica*). In addition, to test the feasibility of carrying frozen cells, we had two cryogenic tubes (1.8 mL) containing frozen cells. The first block was intended to be kept at 20 ºC and the second block was kept at approximately 30 ºC. During flight, the temperature inside the second block of the NanoLab was initially 28°C but degraded over time before the Arduino instructed the thermal heating pads to start working which resulted in short spikes of increasing temperature over time, finally the temperature being close to 23°C. The frozen cells were kept outside of the NanoLab. The ERHASER team observed that 10 of the 32 tubes with cells experienced a change in color which can be attributed to the rapid changes in temperature during the four hours of flight. The cells which underwent temperature shock were the ones placed in the avionics section of the NanoLabs and not directly over the heating pad. This can be attributed to the lack of heat transfer by convection due to low density of air at the cruising altitude of the WB-57 aircraft. The two cryogenic tubes placed on the outside of the NanoLabs and exposed to the outside air temperature had the same indication of temperature shock. Further analysis of the cells will be presented in a future scientific publication.

Student Survey Results for the ERHASER Project

This project was incorporated into the CSO 390 class (Payloads and Integration) as part of the Spaceflight Operations program in fall 2017. Hardware and equipment were funded and supported by the CoE and CoA. Students used various labs to conduct various tasks in this project: The Payload Lab in the CoA, the Engineering Physics Propulsion Lab in the CoAS, and the Structures Lab in the CoE. During this multidisciplinary academic and research project, students developed a set of very unique skills. Table 1 shows an adapted student survey[7] to 13 students that took this class. Over 75 % of the students were pursuing careers in science and Mathematics, and near 25% were in aerospace engineering. Overall, results indicate students had a positive and productive experience working in this multidisciplinary project. Some of these skills learned are:

- Improved their managerial team skills and their hands-on skills measurably when interacting with such a large group of students with different backgrounds with varying skill sets (Aerospace Engineering, Aeronautical Sciences, Computer Science, Mechanical Engineering, and Space Flight Operations).
- Enhanced their project and time management skills when interfacing different electrical components, such as ADS-B, Arduinos, Asus Tinkerboard, and various active thermal sensors (edl-4S, EL-21CFR-TP-LCD, silicon thermal pads, solid state relay vs. transistors, thermocouples) and current passive thermal technologies (aerogel); and NASA's TimePix radiation detector[4], which measured the linear energy transfer (LET) by high-energy particles (HZE) and its contributions to the galactic cosmic rays (GCR) dose[5].
- Used 3D printing technology to print flight hardware (12U NanoLab) aboard WB-57 aircraft. The material was acrylonitrile-butadiene-styrene (ABS) premium and was approved by the NASA team. Students learned the importance of using various materials with various tolerances. This NanoLab has been matured from its first steps toward sending a suborbital payload[6] aboard Blue Origin' New Shepard in 2017.
- Enhanced their lab setting skills using basic equipment, such as basic machine shop skills for the fabrication of the rig, CAD modeling for the design of the 12U NanoLab, soldering for the bGeigie nano safecast radiation device, voltmeter.
- Strengthen documentation of pre-flight operational procedures[6].

Table 1: Student Survey Results

Questions	Responses					
	Engineering			Science and Math		
1. What option mostly reflects your major?	23.7%			76.3%		
	1		2		3	
2. Approximately how many semesters did you participate in ERHSASER? (If you worked on the project over the summer, count that as a semester)	61.5%		23.1%		15.4%	
	Strongly Agree	Agree	Neither Agree or Disagree	Disagree	Strongly Disagree	N/A
3. Participating in this project was a valuable use of my time	61.5%	23.1%	7.7%	-	-	-
4. My interest in pursuing a career in STEM has increased	69.2%	15.4%	15.4%	-	-	-
5. I am more interested in pursuing a career in science or engineering	30.8%	38.4	30.8%	-	-	-
6. This project provided the opportunity to improve my ability to apply knowledge of mathematics, science, and engineering	61.5%	30.8%	7.7%	-	-	-
7. This project provided the opportunity to improve my ability to design and conduct experiment, as well as to analyze and interpret data	46.2%	30.8%	7.7%	7.7%	-	7.7%
8. This project provided the opportunity to design a system, component, or process to meet desired needs within realistic constraints has improved	76.9%	15.4%	7.7%	-	-	-
9. This project provided the opportunity to improve my ability to function on a multidisciplinary team	69.2%	15.4%	15.4%	-	-	-
10. This project provided the opportunity to improve my ability to identify, formulate and solve engineering problems	69.2%	15.4%	15.4%			
11. This project provided the opportunity to improve my understanding of professional and ethical responsibility	46.2%	38.5%	15.4%	-	-	-
12. This project provided the opportunity to improve my ability to communicate effectively	23.1%	61.5%	15.4%	-	-	-
13. This project provided the opportunity to broaden my understanding of the impact of engineering solutions in a global , economic, environmental, and societal context	53.8%	30.8%	7.7%	7.7%	-	-
14. This project provided the opportunity to improve my recognition of the need for, and an ability to engage in life-long learning	53.8%	23.1%	23.1%	-	-	-
15. This project provided the opportunity to enhance my knowledge of contemporary issues	46.2%	30.8%	15.4%	7.7%	-	-
16. This project provided the opportunity to improve my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice	46.2%	23.1%	23.1%	-	-	7.7%

Concluding Remarks

The major learning outcomes of this project related to the design, fabrication and operation of the payload and the instruments utilized are as follows:

- There was a significant learning curve required to understand the intricacies of developing an Environmental Controlled Life Support System (ECLSS) and working with in-vitro biological agents. Further optimization of the thermal system will be considered in the future.
- The team gained crucial experience in developing an airworthy payload and working with the mechanical and electrical subsystems.
- From the first experiment, the team also got a better understanding of the functionality and implementation of ADS-B technology for research and mapping of flight corridors for point-to-point suborbital transportation. The flight path of the WB-57 (NASA927 aircraft) can be visualized and obtained from FlightAware[8] to map the proposed ADS-B ground-based transceivers along the Gulf of Mexico near future spaceports. The ADS-B flight data is still being analyzed.
- The second experiment provided valuable insight towards atmospheric radiation at high altitude and its effect on T-cells when suspended in a cytokine medium kept at a stable temperature.
- One of the main lessons the team learned was how to integrate an instrument using multiple disciplines and utilizing the resources provided to the team in a short period of time to achieve the experimental objectives. Various radiation doses were recorded during the ascent, cruise and descent segments of the WB-57 path, recording instances of spikes of about 48 micrograys or 4.8 mrad. Further radiation assessment is currently being conducted.
- Future changes to the experiment would include a new iteration of the design for the 6U NanoLabs which would allocate a larger volume of space for placing the components of the ECLSS and the instruments inside.
- A key change to the payload would be the cable management for the instruments. The new approach for better cable management would be to wrap the wires in braided flex sleeves which can be secured to the payload rather than each wire being routed individually.
- Another change would be to make a make a circuit breaker bank which is placed inside the payload rather than having individual circuit breakers spread over the major power connections.
- Furthermore, the wiring could also be improved by mounting the female 16 pin connectors to the structure and having the wiring to the aircraft in a separate set of wiring, this would allow for mobility of the experiments by not requiring both structures to be moved at the same time.
- Another form of improvement could be in the testing of instruments under all circumstances including temporary loss of power, sensor and hardware related faults would also help to plan for contingencies, so all the data can be recovered.
- Finally, data redundancy would also be improved by placing additional sensors such as IMU, pressure sensors and CO2 sensors which duplicate the function of the commercial instruments in certain aspects.

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Ankit Rukhaiyar
Ankit is a junior studying Aerospace Engineering (Astronautics) at Embry-Riddle Aeronautical University. Ankit served as the student lead for the ERHASER project which was part of the NASA SOAR program and coordinated with all student teams involved in the project from ERAU. Ankit's project experience stems from working in the Engineering Physics Propulsion Lab (EPPL) where he is part of a multidisciplinary team working on several research projects involving spacecraft design and fabrication, propulsion and system integration.

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Jonathon is a junior studying Aerospace Engineering with a concentration in astronautics from Embry-Riddle Aeronautical University. Jonathon was the team lead for the structures team on the ERHASER project for the NASA SOAR mission. Jonathon has been working in the Engineering Physics Propulsion Lab (EPPL) for a little over two years and has ample experience in a multitude of different projects ranging from propulsion to structural design.

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Nicholas is a junior studying Spaceflight Operations with a concentration in science and technology from Embry-Riddle Aeronautical University. Nicholas managed the radiation monitor alongside with one of the ERHASER's NASA mentors, Kerry Lee. Having basic understanding in UNIX based operating systems and integrated computing systems, Nicholas also managed the on-board computers used to store the data collected by the LitePix radiation monitor.

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Kristina is a cancer researcher with multidisciplinary training and extensive laboratory experience. She obtained Master's Degree in Educational Psychology from the University of Houston and M.S. in Biomedical Science from the Medical University of South Carolina. She is currently enrolled in the Translational Science and Clinical Investigation doctorate program at the University of Texas Health Science Center at San Antonio. She also serves as the lead scientist on few ongoing suborbital experiments.

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