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Progressive project-based learning program for collegiate rocket engineering

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The UCLA Mechanical and Aerospace Engineering department has initiated a project-based learning program wherein students linearly progress in rocket engineering skills development, safety competence, and system complexity from year to year. The program was created in response to significant growth in undergraduate participation and enthusiasm for rocket-oriented engineering projects and inter-collegiate competitions, with accompanying concern for student safety. The program begins with an introductory course on the engineering process involving low-power solid propellant rockets, where after students progress to high-power hybrid and liquid rocket systems over a 2–3 year period, gaining incremental experience and technical competence along the way. Safety training modules before and in between projects provide critical awareness of risks and potential hazards associated with increasingly complex rocket propulsion systems. Furthermore, the program structure encourages mentoring of younger students by those more experienced, reinforced through leadership selection. The program has evolved over a three-year period at UCLA, and has most recently had approximately 120 active student participants.

I. Introduction

STUDENT-ORGANIZED rocket engineering projects at the university level have become increasingly popular and numerous in the past decade, evidenced by the rapid growth in participation at the annual Intercollegiate Rocket Engineering Competition (IREC) held in New Mexico [1]. Increased student interest in rocket engineering may be attributed to an emergence of numerous small-satellite launch start-ups, excitement around high-profile market entrants such as SpaceX and Blue Origin, and a generally healthy aerospace hiring environment. With growing membership and resources within university rocket groups, students have sought more technically challenging projects. Several university groups have set the goal of launching their student-built rocket to space [2, 3], and some have initiated complex high-power liquid rocket projects [4, 5]. Such ambitions inherently involve risks associated with the combination of large quantities of propellant energy and a lack of professional training or experience with more sophisticated rocket propulsion systems. This is particularly concerning for student groups that lack meaningful university oversight, and have initiated highly ambitious technical projects (e.g. launching a liquid bi-propellant rocket to space), with little or no prior experience. In an effort to address such concerns without overly dampening student enthusiasm, UCLA has introduced a progressive project-based rocket engineering program that structurally enables students to rapidly but incrementally gain experience, practical engineering skills, and safety awareness in the context of rocket systems.

II. Programmatic Overview

Student progression through the UCLA rocket engineering program involves staged introduction of propulsive power, total impulse, altitude, and complexity wherein students must complete stepped training to move from one project to the next. Figure 1 illustrates the student progression starting with a formal design project course involving low-power solid propellant rockets, utilizing a commercial propulsion system, and progressing (with steps in between) to a high-power liquid bipropellant project with a student-built propulsion system. Figure 2 provides a more visual timeline of student progression through the program by depicting the physical sizes of the rockets being built relative to the students, with specific unique components of the rockets annotated. As the rockets become more complex and powerful, larger groups of students must work together safely and responsibly, with an increased level of forethought into project management, system design, and testing procedures. The UCLA rocket engineering program encourages

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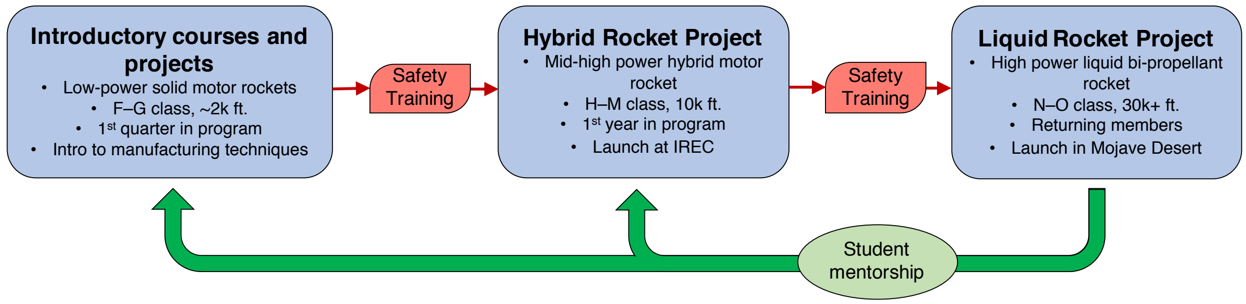

Fig. 1 Student path through progressive rocket engineering program

teamwork and critical design review from the earliest stages, with the aim to foster a healthy mentorship environment in which students help each other achieve increasingly ambitious engineering feats in a safe and incremental manner.

A. Introductory low-power solid rocket projects

New students (including freshmen and transfers) interested in joining the UCLA rocket engineering group must complete a formal course, entitled E96:RISE, to learn the basics of rocket engineering including flight dynamics, component integration, composite manufacturing, solid-propellant ignition, and launch field safety. The course is a scaled-down version of UCLA's aerospace engineering senior capstone design course [6], and the project is considered an introductory engineering experience which exposes first-year students to a real engineering project in the context of their concurrent enrollment in predominantly math and physical science courses. The course utilizes a commercial-off-the-shelf (COTS) solid rocket motor in the F–G impulse class and follows the National Association of Rocketry (NAR) safety code in materials and procedures [7]. Typical target apogees are in the 1,500–2,000 ft range. Senior members of the rocket group—compensated as department teaching assistants for 4 hours per week—provide weekly lectures on topics of rocket engineering and the new students work on the low-power rocket project in teams of 4 or 5 students each. The course is offered over a single academic term (usually fall quarter at UCLA) and is unit-credited as of Fall 2019.

During the project, students are introduced to the engineering concepts of free-body diagrams, aerodynamics, stress and strain, and energy conservation in the context of flight trajectory, materials selection, light manufacturing, and launch safety. In the process, students learn basic skills in computer-aided design (CAD) and data analysis; specific software tools used in Fall 2019 include SolidWorks and OpenRocket. Students also learn how to use light- and additive-manufacturing equipment such as laser cutters for wood, waterjets for metal, and 3D printers for plastic. Equipment and space is provided by the Department of Mechanical and Aerospace Engineering's Aerospace Design Laboratory and the School of Engineering and Applied Science's MakerSpace, a student-operated workspace with light manufacturing tools. Further detail on resources associated with the program is provided in Section V.

B. Mid-to-high-power hybrid rocket project

Students completing the introductory solid rocket course may elect to move into a hybrid rocket project geared towards new rocket club members, with some more experienced students providing leadership and mentoring. This project typically involves a custom-fabricated hybrid propulsion system using nitrous oxide (N_2O) as the oxidizer, and a solid hydrocarbon (often HTPB) as fuel, based on a COTS specification (Contrail Rockets). The motor is typically of the K–M impulse class to support a target apogee of 10,000 ft for the IREC competition. Safety awareness in nitrous oxide propellant handling and remote fill-and-fire procedures (Tripoli guidance [8]), as well as general machine shop safety competence are required increments in training for the more complex hybrid system. This training and guidance are provided by senior members of the rocket group. Further details about the training are discussed in Section III.

In this hybrid project, which typically begins in earnest during the winter quarter of the academic year, students learn new aspects of metalworking/machining, pressure-vessel testing, and fluid handling/plumbing. They also develop custom parachute deployment systems and payloads, as well as electronic control and data acquisition systems, experiencing more interdisciplinary applications of engineering concepts [9]. Relative to an entirely student researched and designed (SRAD) system, the COTS-based propulsion system provides a reliable benchmark around which the students can design the rest of the rocket, ensuring a quick transition to the testing phase. It is during this testing phase that students become

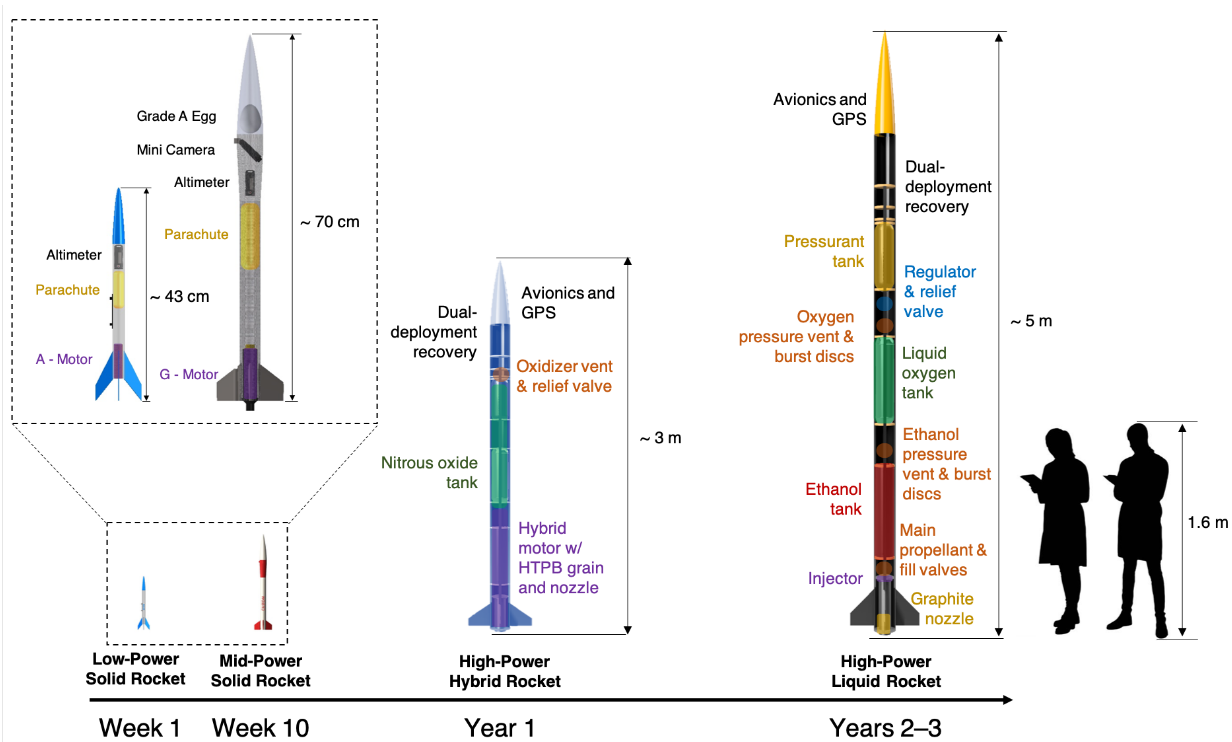

Fig. 2 Chronological progression of rocket size, power, and complexity, relative to student size.

more comfortable with cold-flow and hot-fire procedures while developing safe habits in component manufacturing and testing.

Prior to competition, the student group is required to qualify their motor through a static hot-fire test in which oxidizer tank pressure is monitored and motor thrust is measured. These testing requirements motivate students to develop real-world instrumentation, and to familiarize themselves with pressure transducers, thermocouples, and load cells, all of which are commonly used in engineering industry. These tests provide both procedural and safety experience for the students as well as performance data with which the students can plug into their flight and trajectory simulations to ensure a safe launch (sufficient off-the-rail speed). Despite being driven by mostly new students, the hybrid rocket project has demonstrated technical success—in 2018, the UCLA hybrid rocket project placed second in its category at the Spaceport America Cup (or IREC) competition with a team comprising almost entirely freshmen.

C. High-power liquid rocket project

Students with at least one year of experience (having completed the solid and hybrid projects) can progress to a more advanced high-power liquid bi-propellant rocket project. This rocket project entails a student-researched-and-designed (SRAD) liquid oxygen and ethanol propulsion system [10], with an N–O impulse class, targeting an apogee of 30,000 ft or greater. The project involves additional technical elements of cryogenics handling, welding, supersonic flight dynamics, and CNC machining. Fluid handling and delivery systems are also much more sophisticated (and more than double in scale) compared to the hybrid project with more precise timing, pressure regulation, and valve actuation needed for successful hot fire and launch. Safety awareness in cryogenics handling is an important increment in training for the liquid system. The project culminates in the launch of the liquid bi-propellant rocket in the Mojave Desert at the end of the academic year. Over the past two years, UCLA has launched three liquid bi-propellant rockets (with the most recent hitting a student-record apogee of ~15,000 ft.), but has yet to complete a system recovery. More detail about the liquid rocket project is detailed in a previous paper [4].

III. Safety Training

The student path through the UCLA rocket projects involves important steps of safety training. Historically (with smaller groups of students), training had been handled by student word-of-mouth with occasional review by campus safety and a lack of documentation. To complement the new progressive rocket engineering program, new formal safety training sessions and modules have been developed and introduced. This includes a general rocket engineering safety training session to be completed by all members entering the club, and specific training modules on propellants, cryogenics, pressure-vessels, and metalworking. Additional in-person training is important to supplement the online safety modules and support the safety of students performing complex heavy manufacturing or conducting fill-and-fire procedures. The recommended in-person training is shown in the context of the online safety modules in Figure 3, and detailed in the subsections that follow. Notably, department and university staff have helped develop and provide convenient access to the training modules with record-keeping tools, as well as the curriculum described herein, giving student leaders new and better tools to enforce and monitor training.

A. Online Environmental Health & Safety Modules

A summary of the modules available through the WorkSafe website of UCLA's Environmental Health & Safety (EH&S) is provided in the left of Figure 3. The modules are divided into two parts, Fundamentals of Rocket Engineering Safety (4 modules), for all members of the rocket group, and Advanced Rocket Engineering Safety (3 modules), for students joining either the hybrid or liquid rocket project competition team. Module completion is tracked online by UCLA EH&S, and student members are not permitted by student leadership to engage in successive rocket engineering activities without completing the modules online or providing verification of module completion.

1. Fundamentals of Rocket Engineering Safety

Students joining UCLA's progressive rocket engineering program are first introduced to safety standards, emergency preparedness, and laboratory equipment in a Laboratory Orientation, which is primarily informative about UCLA-specific facilities. Following the orientation, students learn about Personal Protective Equipment (PPE), as well as some of the hazards they protect against. In particular, emphasis is placed on appropriateness of certain types of PPE during different parts of the rocket engineering program. Students then learn about Light Manufacturing methods, which are used in all of the rocket projects, even to construct the small rockets in E96:RISE. In this module, students learn about the hazards of hand and power tools, as well as cutting tools and some chemical adhesives. The final module in the Fundamentals of Rocket Engineering Safety series covers Field Safety, and is intended to prepare students for their first of many trips to testing facilities in the Mojave Desert. Covered topics include weather hazards, as well as an introduction to established safety codes, and specific dangers to look out for while spectating other launches.

2. Advanced Rocket Engineering Safety

Students continuing with the progressive rocket engineering program and joining the hybrid rocket project must complete an additional three online safety modules. These three modules are specifically designed to provide safety information in the context of the actual rocket systems that the students will encounter, with particular emphasis on the hazards associated with fluid systems and propellant handling.

The first of these advanced modules covers hazards associated with Fluid Systems, including pressurized vessels, material compatibility, and fluid system components such as different types of valves and regulators. The purposes of each fluid system component are discussed in detail to provide context for appropriate usage—for example, burst discs are covered in the context of preventing catastrophic pressure vessel failure. Different fitting types are discussed, as well as hazards of leaks and foreign object debris (FOD)—common culprits in many student-built rocket failures.

Subsequently, students learn about Chemical and Propellant Safety, covering safety notation, and fire, acid, corrosive, and cryogenic hazards. Students are also taught how to read Material Data Safety Sheets (MSDS). Special attention is paid to cryogenic liquid oxygen and nitrous oxide, since these are the oxidizers utilized by the student rocket group. PPE required for handling these substances is re-iterated to support student retention of the information.

The final module covers High-Power Tests and Launches, and is intended for students preparing for their first competition rocket launch. Special attention is paid to the differences between PPE, engineering controls, and administrative controls. Specific examples are provided to guide students in coming up with safer designs (engineering controls) and procedures (administrative controls). Requirements for safe fill-and-fire and launch are discussed in reference to established rules and regulations for high-powered rockets.

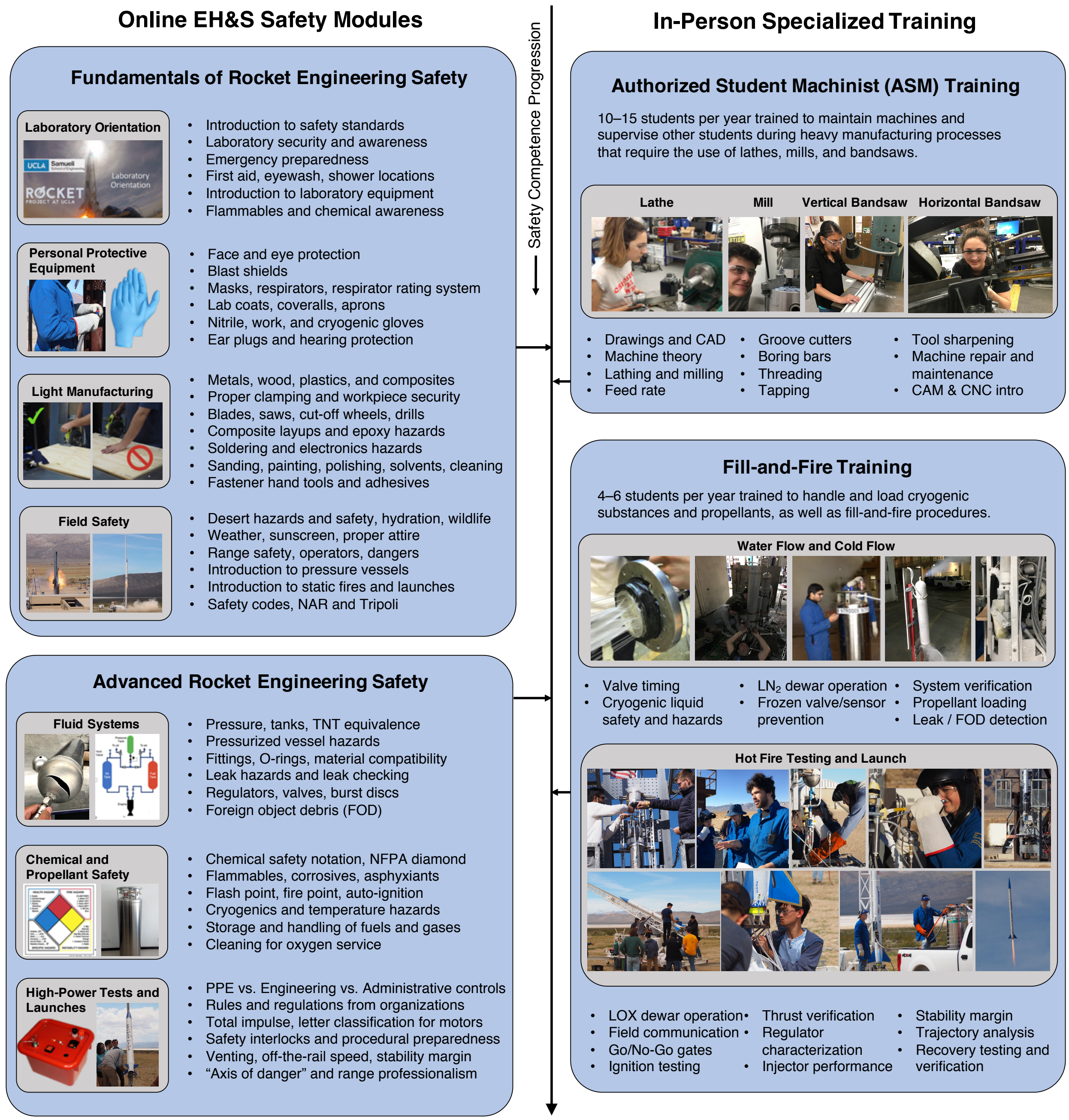

Fig. 3 Flow chart describing the student progression through the safety modules (left) and in-person training (right) during the progressive rocket engineering program. Covered topics for each module and training detailed in bulleted lists. All persons photographed are UCLA affiliated students.

B. In-Person Specialized Training

1. Authorized Student Machinist (ASM) Training

Each successive rocket project in the program requires a greater number of custom-manufactured components than the previous rocket projects, necessitating increased usage of heavy manufacturing and metalworking techniques. At minimum, required equipment includes lathing and milling machines, as well as bandsaws and associated tooling. Manufacturing of many components can be accelerated with the use of waterjets and CNC machines, though these are not strictly necessary. The usage of these machines not only requires substantial caution and safety awareness from the beginning, but also guided training from more experienced machinists. For student safety, all heavy machines are locked out of power, with only trained students receiving keys to unlock the machines and supervise their usage.

At UCLA, 5–15 students per year (based on interest) are trained in heavy machine usage in an Authorized Student Machinist (ASM) program, depicted in the top right of Figure 3. The in-person training, which lasts one quarter, is led by a senior member of the rocket group with exceptional machining experience, and includes lecture components covering machine theory, computer-aided design, and drawings, as well as laboratory demonstration and mastery components covering various metalworking practices. Additionally, students are trained in machine maintenance, and are introduced to CNC manufacturing. Throughout the quarter, students-in-training manufacture a miniature bi-propellant injector using all of the different types of machines in the student shop; this project encompasses nearly all relevant machining operations that will be encountered during the rocket engineering program. At the end of the training, the student-in-training must teach a volunteer student with less experience how to manufacture a simple part. Once the training is complete, the students are considered an ASM, and can check out a key to unlock the machines and mentor other students in their usage. No student machining is permitted without an ASM present, and ASMs must return their keys at the end of the academic year.

2. Fill-and-Fire Training

For both the hybrid and liquid rocket projects, a strong emphasis is placed on on-campus testing, in order to increase the likelihood of success in the field and reduce costs associated with unsuccessful field tests. Hot fire testing and launches are conducted off-campus at both the Mojave Test Area (MTA) of the Reaction Research Society (RRS) and the Friends of Amateur Rocketry (FAR) test site near Cantil, CA in the Mojave Desert under the supervision and guidance of a pyrotechnic operator licensed by the state of California with experience conducting tests using liquid propellants. These test sites are equipped with test pads, launch rails, bunkers, and radio communication systems.

On-campus testing includes water flows to characterize discharge coefficients of the system plumbing, and low-pressure helium leak checks to locate problematic leaks in the system. Pressure drops during waterflow tests are measured by using differential pressure transducers and mass flow rates are recorded by catching the outlet water in a bucket and weighing the amount captured over some specified time interval. This allows students to gain experience in characterizing real fluid systems while also encouraging detailed analysis of the propulsion system, in addition to detecting and catching FOD in a safe manner. Cold flows are also conducted on campus, using inert substances instead of propellants, so that students can practice the fill-and-fire procedures beginning with leak checks and propellant fill to countdown and "ignition" while confirming instrumentation reliability. For the liquid rocket project, these cold flow trial runs involve using liquid nitrogen instead of liquid oxygen and water instead of fuel. These tests determine the reliability of the fluid handling system at cryogenic temperatures—an otherwise unforeseen complication in many student-originated designs. Moreover, the cold flow tests allow students to become comfortable with and refine their testing procedures in a safe manner, thus dramatically reducing the likelihood of preventable hazards in the field.

During the static tests of the hybrid rocket project, students become familiar with field communication (bunker-to-pad), real-world instrumentation performance, and technical problem solving. The importance of pressure vessel and propellant safety is specifically highlighted, as nitrous oxide must be filled remotely under pressure in order to assume a liquid form in the hybrid system's oxidizer tank. This mitigates hazards associated with local propellant loading, increasing students' awareness of the risks associated with hot-fire testing and encouraging safe habits, such as keeping distance from pressurized vessels and developing methods to check for problems remotely through instrumentation rather than in-person. Decision gates become especially relevant during hot-fire attempts, and the students develop an intuitive sense of when to abort a test or move forward. Students typically conduct approximately 3–5 hot fires per year to both become familiar with the procedures using a COTS system and to confirm the thrust required to achieve a safe off-the-rail speed using a custom-built system.

During the first static fire test of the liquid rocket project in an academic year, a group of 4–6 students is trained to handle and load liquid oxygen by the pyrotechnic operator, and all participants are made aware of the real-world risks associated with liquid oxygen. Because the liquid rocket is loaded with propellant locally rather than remotely, a much more rigorous procedural regiment is necessary to mitigate personnel hazards. Following plumbing and instrumentation checks, the pad is evacuated and a readout of the procedures is given, with input from the pyrotechnic operator, if necessary. Under no circumstances are more than 6 people on the pad during propellant loading. This is critical to avoid miscommunication and cross-talk, as well as minimize personnel risk. Fuel (ethanol) is loaded into the fuel tank, and the LOX dewar fastened to the back of a pickup truck is brought to the pad. Guided by the pyrotechnic operator, two students wearing appropriate PPE (face shields, safety glasses, flame-resistant lab coats, cryogenic gloves) load liquid oxygen into the oxidizer tank while another student reads through the procedures, as shown in the bottom right of Figure 3. One student operates the dewar while the other is responsible for connecting and disconnecting the cryogenic loading hose from the rocket propulsion system. The students use fixed wrenches to attach and detach the plumbing, to avoid ignition hazards associated with grease often used in adjustable wrenches. Following the propellant loading, all personnel evacuate the pad into the bunker and the LOX dewar is removed as well, after which the system is pressurized and countdown starts. After the hot-fire test, the engine is examined to determine injector performance (i.e. detect any unforeseen hot-spots), and the students quickly assess the results of their work. Students typically conduct 2–3 hot fire tests per academic year to become trained with propellant loading and subsequently test new or improved hardware to optimize thrust. The emphasis of student manufacturability of the systems allows students to quickly iterate on any design or procedural failures, enhancing their engineering intuition and improving chances of a successful launch. More information about the procedures in the liquid rocket project is available in a previous paper [4].

IV. Aerospace Career Preparation and Job Placement

Design reviews are an important feedback mechanism in the aerospace industry, and thereby a preparatory component of student projects. Exposure to the review process in the progressive rocket engineering program at UCLA begins early. In the introductory E96:RISE course, student mentors conduct a Preliminary Design Review (PDR) and Flight Readiness Review (FRR) for each student group, providing an early introduction to the engineering design feedback process, public speaking, and results dissemination in a supportive peer-based environment. These reviews, based on industry practices, are intended to establish a culture of advice-seeking and critical analysis of design choices; these foundational attitudes provide a basis for success in the hybrid and liquid rocket projects that follow.

A preliminary design review, critical design review, and test/flight readiness reviews are scheduled during each of the hybrid and liquid rocket projects at predetermined intervals ahead of their respective competitions to provide students an opportunity to receive feedback from industry professionals. Although UCLA MAE requires these reviews to ensure continued funding of the projects, the student project leader(s) themselves must assume responsibility for scheduling, reviewer invitations, presentations, analysis, and design proposals. This serves to accelerate student leaders' management responsibilities and professional development while creating a personal stake in the professionalism of the presentations [11].

Department involvement encourages more interaction between faculty and the student leaders, increasing opportunities for aptitude recognition and recommendation for both graduate studies and industry jobs. Additionally, many industry reviewers are alumni of the rocket group and/or are actively recruiting top students for industry job opportunities. Since the introduction of the progressive rocket engineering program in mid-2017, 20 of its students have graduated from UCLA engineering. Of the 20 graduates, 6 are currently attending or will attend (in 2020) graduate studies, 1 is attending Officer Candidate School for the U.S. Navy, and the remainder are employed by major aerospace companies (SpaceX, Raytheon, Blue Origin, Boeing, Northrop Grumman, Lockheed Martin, Aerojet Rocketdyne, others) across the United States, with most located in Southern California.

V. Cost and Resource Summary

The student rocket engineering program described here requires specific resources (funds and facilities) for success. Depicted in Figure 4, students have access to approximately 120 m^2 of manufacturing and assembly space through the Department of Mechanical and Aerospace Engineering in the Aerospace Design Laboratory, with access to computers with CAD software, lathe and mill machines, a waterjet, 3D printers, workbenches, toolboxes, gas cylinder and liquid N_2 storage, and a projector screen to hold student meetings. This is a shared department space used for project-based course instruction (e.g. capstone courses). Organization and maintenance are shared between the students and the MAE Department. In a nearby engineering building, the students also have access to the 836 m^2 UCLA MakerSpace, which is

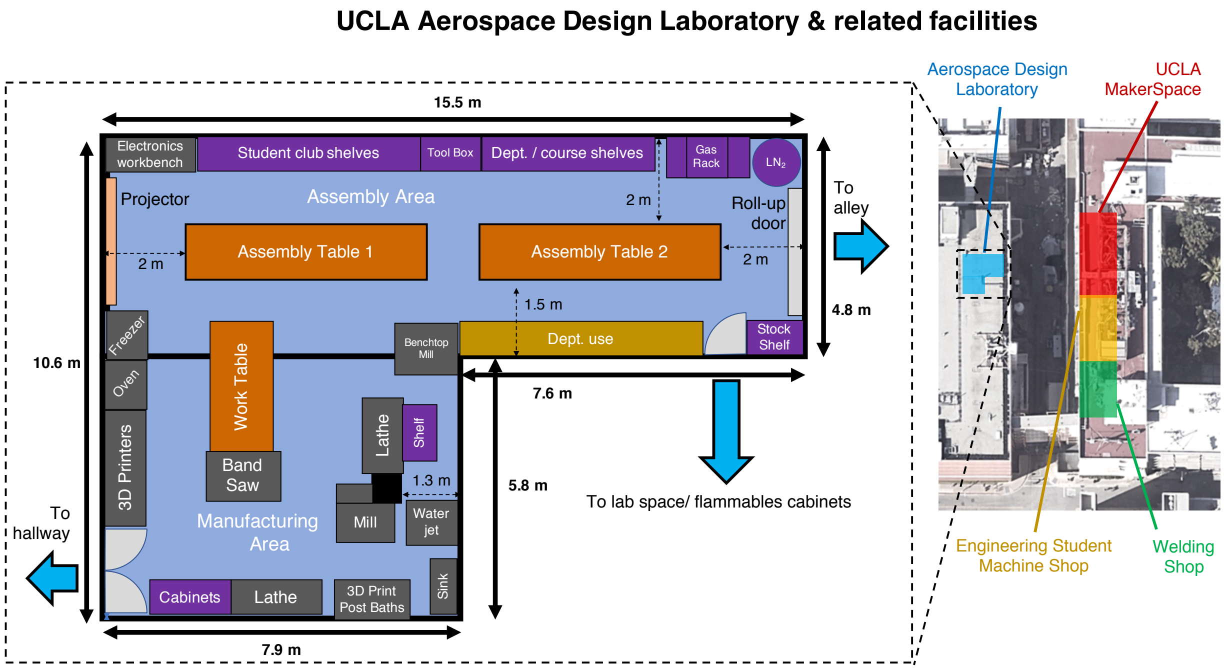

Fig. 4 Overhead view of the UCLA Aerospace Design Laboratory (left), with assembly tables, storage, and equipment shown. Location within UCLA engineering also shown (right), with relative locations of the UCLA MakerSpace, Engineering Student Machine Shop, and Welding Shop also depicted.

shared by all engineering departments at UCLA. The space includes 3D printers, laser cutters, tools for light machining, circuit board printers, electronics fabrication and test equipment, and a reflow oven. Heavy machining tasks which are too complex for beginning students can be performed by the students under the guidance of professional machinists in the Engineering Student Machine Shop, which is also conveniently located nearby. Additionally, several components of the rocket projects often require metal welding, performed by a professional welder in the nearby campus Welding Shop. The proximity of these resources to the student workspace facilitates project progress while also encouraging students to develop good working relationships with professional university staff in a manner reflective of their anticipated experiences in industry.

A table summarizing the costs of the program in 2019 U.S. Dollars is shown in Table 1, separated by the introductory E96:RISE course, the hybrid rocket project, and the liquid rocket project. Approximately half of the funds for the hybrid and liquid rocket projects are sourced from corporate sponsorship, which is typical of student-run organizations building vehicles for inter-collegiate competitions.

Budget for the E96:RISE course is approximately 6400 USD per quarter, with approximately half of the costs going to compensation for student mentors, and about 20% of the budget going to launch day logistics. Launches are held at Santa Fe Dam approximately 60 km from UCLA on a Saturday near the end of the quarter, and the MAE Department rents passenger vans, driven by student mentors, to ensure all of the students can participate. Notably, these costs roughly scale proportionally to number of students enrolled in the course, and comes out to approximately 145 USD per student.

The hybrid and liquid rocket project budgets depict more granularity in the materials costs, with the bulk of the budgets going to procuring/building the propulsion system and hot-fire testing in the Mojave Desert. The costs for the airframe, avionics, and the recovery systems of the rockets are largely the same, because the overall structure of the rocket is not fundamentally different between the two systems. Travel and lodging for IREC in New Mexico make up a significant portion of the overall hybrid rocket project budget, although this portion is partly self-funded by students who have personal interest in attending the competition. Historically, 40–50 students have attended the competition every year, representing a cost of approximately 110 USD per competition rocketeer.

Materials and testing budget for the liquid rocket project propulsion system is approximately double that of the hybrid rocket project propulsion system, indicative of the increased system size and complexity shown in Figure 2. Much of the higher cost is due to a larger number of fluid systems components such as valves and regulators. Moreover,

Table 1 Operating budget for student-led rocket engineering projects at UCLA

Rocket Project	Description	Cost in 2019 USD
E96:RISE	Student mentors (160 student-hours)	3,200
(Solid rocket project)	Materials	2,000
	Launch day transportation (44 students)	1,200
	Introductory course total (1 quarter)	**6,400**
Hybrid rocket project	Propulsion	2,400
	Avionics & recovery	1,100
	Airframe	500
	Hot fire testing (4 tests)	2,000
	Travel and lodging for competition (50 students)	5,500
	Hybrid rocket project total	**9,500**
Liquid rocket project	Propulsion	4,100
	Airframe and recovery	1,260
	Avionics	980
	Hot fire testing with licensed Pyro-Op (4 tests)	4,000
	Travel for competition (30 students)	2,000
	Liquid rocket project total	**12,340**
All projects	Lab expendables and maintenance	2,000
	Total	**30,240**

hot-fire testing with the liquid rocket project is performed under the guidance of a pyrotechnic operator licensed by the State of California with experience conducting tests with liquid oxygen. More detail about the costs of the liquid rocket project are provided in a previous paper [4].

Continued operation of the shared labspace requires occasional replacement tooling, machine oil, waterjet maintenance, hand tool replacement, and cleaning supplies. Included in these costs are replacement dust masks, respirators, nitrile gloves, ear plugs, safety glasses, and other PPE which are disposable or otherwise damaged over time.

VI. Conclusions and Ongoing Program Development

A progressive rocket engineering program has been initiated at UCLA to accommodate growing student interest and ambition while aiming to maintain safe practices, program cohesion, and continuity. Within the new program, students take incremental steps in technical sophistication and rocket total impulse that allow for layered experience and intuition for safe engineering. The program focuses on student-manufacturable designs which quickly allow students to get to the test phase, where they can experience how theoretical classroom-learned concepts are realized or broken in reality.

Building and maintaining such a program is not without challenges; limited faculty/staff time and resources and historical autonomy of student-run organizations necessitates careful consideration of student leadership to ensure optimum student mentorship while encouraging safety and maintaining department insight. Previously, the small sizes of student clubs meant that the design and construction of launch vehicles were performed by only a few technically-savvy and dedicated students. As such, project and subteam leaders were typically highly technically skilled, but less adept at overall project management and task delegation. As these organizations and project scopes grow in size, student leaders with better management and communications skills are needed to ensure group cohesion and productivity.

A balance between student enthusiasm and educational effectiveness must be struck to ensure student success in the context of graduation and turnover; ambitious projects spanning longer than an academic year (approximately 9 months) have historically been unsuccessful or have floundered in the design phase without achieving a hot-fire test or launch prior to student graduation. This can reduce overall progammatic knowledge-retention, as students entering the program in the middle of a multi-year project do not get to experience the initial phases firsthand. Additionally, students' understandable desire for personal ownership and lasting contributions to the organization often encourage dramatic changes away from reliable and proven designs, risking resources and time in an already technically ambitious and time-constrained project. The low cost, robustness, and short build times of the competition rocket designs presented here allow for students to spend more time re-engineering based on testing feedback, and enables a design-build-launch process that fits within an academic year. Given the proliferation of similar student rocket groups at other universities, it is anticipated that such a program, once refined, may serve as a model to help other educational institutions navigate similar student-oriented programs.

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References

[1] ESRA, "Experimental Sounding Rocket Association," , 2018. URL `http://www.soundingrocket.org/`.

[2] Dutta, A., Ernst, Z., Buddhavarapu, S., Charlson, T., Seshan, S., and Sublett, J., "The Yellow Jacket Space Program: Insights into Starting a Student Led Space-Shot Rocketry Team at the Georgia Institute of Technology," *AIAA Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2019. doi:10.2514/6.2019-0615.

[3] Aitoumeziane, A., Eusebio, P., Hayes, C., Ramachandran, V., Smith, J., Sridharan, J., St. Regis, L., Stephenson, M., Tewksbury, N., Tran, M., and Yang, H., "Traveler IV Apogee Analysis," Tech. Rep. May, USC Rocket Propulsion Laboratory, Los Angeles, CA, 2019. URL `https://viterbischool.usc.edu/news/2019/05/usc-rocket-propulsion-laboratory-shatters-student-altitude-record/`.

[4] Nair, A. P., Pineda, D. I., Spearrin, R. M., and Crisalli, D. E., "Low-cost student-manufacturable liquid oxygen-ethanol sounding rocket," *AIAA Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics, San Diego, CA, 2019. doi:10.2514/6.2019-0613.

[5] Nilsen, C., Meyer, S., and Meriam, S., "Purdue Liquid Oxygen - Liquid Methane Sounding Rocket," *AIAA Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2019. doi:10.2514/6.2019-0614.

[6] Spearrin, R., and Bendana, F., "Design-build-launch: A hybrid project-based laboratory course for aerospace engineering education," *Acta Astronautica*, 2018. doi:10.1016/j.actaastro.2018.11.002.

[7] National Association of Rocketry, "Model Rocket Safety Code," , 2012. URL `http://www.nar.org/safety-information/model-rocket-safety-code/`.

[8] Tripoli Rocketry Association Inc., "Tripoli High Power Safety Code," , 2019. URL `http://www.tripoli.org/SafetyCode`.

[9] Hotaling, N., Fasse, B. B., Bost, L. F., Hermann, C. D., and Forest, C. R., "A Quantitative Analysis of the Effects of a Multidisciplinary Engineering Capstone Design Course," *Journal of Engineering Education*, Vol. 101, No. 4, 2012, pp. 630–656. doi:10.1002/j.2168-9830.2012.tb01122.x.

[10] Crisalli, D. E., "How to Build a Rocket the Hard Way," *High Power Rocketry*, 1996, pp. 8–68.

[11] Todd, R. H., Sorensen, C. D., and Magleby, S. P., "Designing a Senior Capstone Course to Satisfy Industrial Customers," *Journal of Engineering Education*, Vol. 82, No. 2, 1993, pp. 92–100. doi:10.1002/j.2168-9830.1993.tb00082.x.