Cover Page

Title of Design:

Catch-CO_2: Integration of Carbon Capture Technology on UAS

January 2020 - April 2020

Design Challenge Addressed: Airport Environmental Interactions

University Name: Binghamton University- State University of New York

---

Team Member(s) Names:

Barjak, Thomas	**(Undergraduate)**	tbarjak1@binghamton.edu
Cohen, Eitan	**(Undergraduate)**	ecohen49@binghamton.edu
Flynn, Brian	**(Undergraduate)**	bflynn2@binghamton.edu
Moore, Andrew	**(Undergraduate)**	amoore20@binghamton.edu
Sloan, Zachary	**(Undergraduate)**	zsloan1@binghamton.edu
Tierney, Daniel	**(Undergraduate)**	dtierne2@binghamton.edu
Warner, Jacob	**(Undergraduate)**	jwarne12@binghamton.edu
Weiss, Harley	**(Undergraduate)**	hweiss5@binghamton.edu
Yoo, Joonhwan	**(Undergraduate)**	jyoo45@binghamton.edu

Advisor(s): Professor Chad Nixon, Professor Zachary Staff

CATCH-CO_2

INTEGRATION OF CARBON CAPTURE TECHNOLOGY ON UAS

DESIGN CHALLENGE ADDRESSED:
AIRPORT ENVIRONMENTAL INTERACTIONS

TEAM MEMBERS (UNDERGRADUATES):
THOMAS BARJAK
EITAN COHEN
BRIAN FLYNN
AJ MOORE
ZACHARY SLOAN
DANIEL TIERNY
JACOB WARNER
HARLEY WEISS
JOONHWAN YOO

ADJUNCT PROFESSORS:
CHAD NIXON
ZACHARY STAFF

A REPORT BY

BINGHAMTON UNIVERSITY

STATE UNIVERSITY OF NEW YORK
BINGHAMTON UNIVERSITY SCHOLARS PROGRAM

Executive Summary

Airports looking to adapt and integrate plans for sharing the National Airspace System (NAS) with unmanned aircraft systems (UAS) should consider how these systems can be utilized to improve the NAS itself. One major issue the Federal Aviation Administration (FAA) seeks to solve is poor air quality, both within airport environs and through airspace across the world. The rise in carbon emissions has contributed to poor air quality and resulted in devastating environmental impacts, with the aviation industry contributing up to 2% of Carbon Dioxide (CO_2) in the atmosphere.

The following proposal, compiled by undergraduate students at Binghamton University-State University of New York, seeks to remove CO_2 from the atmosphere by combining carbon capture systems with the rapidly increasing number of UAS. The design itself utilizes electrochemical cells attached to the side of a UAS, which will capture carbon through a chemical process known as adsorption and release it into a removeable storage tank at the bottom of the UAS. The ability to further remove the tank and sell off the carbon will incentivize both consumers and larger corporations looking to adopt UAS technology to buy eco-friendly UAS.

This design considers the many FAA regulations set forth on UAS under and over 55 pounds, as well as UAS safety precautions. If utilized, this proposal will enable wide-scale carbon collection as a secondary function on top of the UAS' primary function, essentially having millions of miniaturized direct-air capture plants flying through the air. As the number of UAS increases and both UAS and carbon capture technologies advance, the capacity for carbon capture will undoubtedly improve, furthering the removal of carbon from the atmosphere and potentially leading to a carbon-neutral or even carbon-negative aviation technology.

Table of Contents

Table of Figures

I. Problem Statement and Background

In recent years, there has been a large push to limit and reduce carbon emissions globally. The build-up of carbon dioxide and other greenhouse gases in the atmosphere has led to a global rise in temperature and the melting of polar ice caps [1]. Rising global temperatures also impact ecosystem and agricultural sustainability. Airports and airlines have already implemented many improvements in the last decade due to the negative effects of carbon emissions; among them are more aerodynamic and fuel-efficient aircraft. Despite this, the aviation industry still contributed up to 2% of overall carbon emissions in 2019 (seen in Figure 1), which equates to 195 million tons of carbon [2], or the equivalent weight of 3 million Boeing 747-800s (assuming a standard weight of 65 tons).

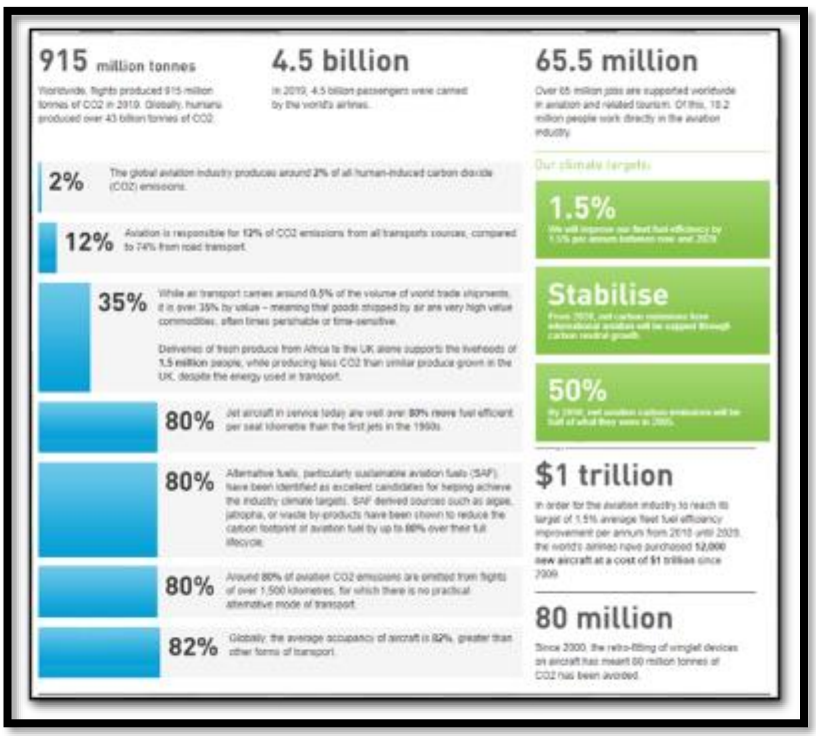

Figure 1- Aviation Emissions [2]

The current forerunners in carbon emission-reduction within the aviation industry consist of biofuels and hybrid electric aircrafts. Biofuels have already been implemented by many European airlines, with some aircraft currently using a 50/50 blend of jet fuel and a biofuel derived from Camelina oil. The aircraft using the hybrid fuel blend had a 50-70% reduction in overall particle emission [3], and its implementation has proven that there is a desire to reduce the carbon emissions resulting from airplanes.

The FAA has made it a goal to reduce carbon emissions and environmental impacts. It is projected that by 2030, carbon emissions will grow to somewhere within the range of 271-401 million tons, reflecting the best and worst-case scenarios respectively [4]. This would translate to a 3%-106% increase in emissions over the next 10 years. Another projection by the Advisory Council for Aeronautics Research in Europe (ACARE) shows emissions growing by at least 75% by 2050.

Therefore, the primary goal of this research is to develop a new method of utilizing UAS to create a carbon negative or carbon neutral approach to reduce carbon emissions in the atmosphere. At the start of 2020, the FAA has reported 1,548,816 UAS currently registered, and of those UAS, 435,189 are commercially registered [5]. In addition to this, several large-scale companies, including the United Parcel Service (UPS) and Amazon, have announced plans to transition to UAS delivery. In 2019, UPS attained the FAA's first full approval for a UAS airline. They intend to utilize this UAS fleet to service healthcare operations before expanding into consumer deliveries after construction of centralized operations control centers [6]. Amazon's Prime delivery service has also put out their mission statement detailing plans to implement a system of UAS to safely deliver packages to their customers in 30 minutes or less [7]. Like UPS' intended system, this would mean the implementation of operations control centers as well as the deployment of a large-scale fleet of UAS.

The objectives of this proposal are to:

- Reduce global carbon emissions utilizing carbon capture technology

- Review literature on the relevant fields of airline emissions, global climate change, current methods of carbon reduction, and UAS use and flight
- Utilize as many of the 1,548,816 UAS currently registered to the FAA [5], and the many more that will be built in the future, to create a carbon negative or neutral solution
- Generate a proof of concept and general design for our proposed solution
- Prove the feasibility of carbon capture technology in the aviation industry

II. Summary of Literature Review

a. Alignment with Mission of FAA

Reducing carbon emissions to mitigate climate change has been an increasingly important goal in many industries, including aviation. When setting long-term goals, the FAA has placed a large emphasis on decreasing the environmental impact of aviation, especially concerning carbon emissions, detailed in Destination 2025 [8]. According to Destination 2025, "Aviation emissions … are on a trajectory for carbon neutral growth" [8]. Efficiency is being targeted in many specific areas of aviation, including the creation of fuel alternatives and the development of more electric aircraft (MEA) and hybrid-electric aircraft.

Biofuels, one type of alternate fuel source, have already been deployed into parts of the European aviation market. Collected data indicates "that the lifecycle carbon saving from moving to biofuels could be up to 80% over that of the traditional jet fuel" [4]. However, biofuel prices are "not expected to be competitive with fossil jet prices" over the short term [4]. Boeing forecasts 4.6% growth in air traffic between 2019 and 2038 [9]. Thus, there is still a large timeframe for carbon emissions to aggregate. While biofuels reduce our dependence upon fossil fuels, "many challenges remain before aviation biofuels can be widely adopted" [3]. Even if biofuel becomes sustainable, burning any fuel still creates CO_2 emissions.

b. Potential of Carbon Capture

Since carbon emissions have already accumulated in the atmosphere, and aviation emissions cannot easily be cut to nothing, capturing carbon dioxide from the atmosphere could be an adequate solution to achieve carbon neutrality. Researchers have proposed a new method for carbon capture using “Faradaic Electro-swing Reactive Adsorption” [10]. An electric flow through such a cell will cause one-ring hydrocarbons to bind with CO_2 through adsorption. When the polarity of electric charge is reversed, the effect is reversed, and the CO_2 is released [10]. While this has the potential to remove carbon from the atmosphere, it does not provide an outlet for any carbon that is captured. Many industries utilize carbon in production, opening the possibility for collected carbon to be sold to such companies. Carbonated beverage plants burn fossil fuels to create carbon dioxide. Farmers with greenhouses often burn carbon-producing fossil fuels in order to feed their plants [11]. If recycled carbon could be supplied to these industries, it would both reduce fuel consumption and provide an outlet for carbon collectors in the aviation industry.

c. Application of Carbon Capture to UAS

Usage of UAS has exponentially grown during the past decade. As of February 18, 2020, 1,552,633 UAS are registered in the United States, of which 436,836 are for commercial usage and 1,112,088 for recreational purposes [5]. Dominant entities in the commercial UAS industry, such as Amazon, are rapidly conducting delivery research to expand the usage of commercial UAS to be as normal as delivery trucks [12]. Calculations on carbon dioxide at different altitude levels indicate that carbon dioxide concentration varies from 964 to 1,000 parts per million (ppm) from 0 to 1,000 feet and decreases as the altitude levels get higher. At 10,000 feet, carbon dioxide concentration is calculated to be 688 ppm [9]. To efficiently capture atmospheric carbon dioxide, capture must occur in altitudes from 0 to 1,000 feet, where carbon dioxide exhibits higher density than other greater altitudes. The FAA guidelines state that most commercial and personal UAS may not exceed 400 feet above ground when flying [13]. Thus, applying the carbon capture method to UAS that operate in the altitudes 0 to 1,000 feet would be ideal to efficiently capture atmospheric carbon dioxide.

III. Problem Solving Approach

The project team was made up of nine students from the Binghamton University Scholars Program. Students were divided into four pairs, each having their own responsibilities within the project, with one project leader overseeing the group.

The project leader took responsibility for the management of the team and the submission of assignments, as well as the completion of their own assignments. The project lead worked closely with all groups, university, and non-university partners to ensure that the project was finished on time and to the best of everyone's abilities. The project lead oversaw four distinct subgroups. The first team, the design team, had the job of describing the project from an engineering, scientific, and technical view. Their responsibilities included writing the Technical Aspects Addressed, which evaluated the proposed design from a technological standpoint, and the Projected Impacts, which examined the possible ramifications of the team's proposal. The second team, the engineering and graphics team, held the responsibility of finding and developing photos and graphics for the final paper to support the proposal. In addition, this group oversaw the development of the cover page; the Problem Statement and Background, which examined the issue the team had chosen; and the Summary and Conclusions. The third team, the risk assessment and research team, was tasked with compiling a summary of all the teams' literature reviews. They also developed the Safety and Risk Assessment section of the paper, which examined the potential risks and safety hazards of the developed system according to FAA guidelines; Appendix A, a list of contact information; Appendix E: Evaluation of Educational Experience, in which they summarized both the students' and educators' perspective on the ACRP design competition; and Appendix F, the full reference list. The final team, the strategies and approach team, researched non-university partners involved in the project and compiled the information they found into Appendix C. This team also recorded the interactions with airport-operators that would eventually go into the report, and documented the steps taken throughout the project for the Problem Solving Approach.

Professors Zachary Staff and Chad Nixon, both adjunct professors at Binghamton University, oversaw the research. A former student of Binghamton University himself, Professor Staff provided the team with guidance and knowledge throughout the process based on his experience in aviation planning. Professor Nixon, also with professional experience in aviation planning, provided additional intelligence that was an essential tool for navigating the research.

On the first day of class, Professor Staff provided an overview of our responsibilities as members of the team and tasked everyone with brainstorming ideas to submit to the ACRP Design Challenge. On Thursday, February 13th, all members of the class participated in a discussion that resulted in two projects to pursue, one of which was this, the use of carbon capture technology in aviation. The team, seen in Figure 2, initially pursued the implementation of carbon capture on passenger and hybrid planes. After discussing the implications and ramifications of such a modification, it was decided that the technology would be useless if incorporated into planes due to the fact that the carbon output produced by the plane would be significantly greater than that which system could capture. Furthermore, strict FAA

Figure 2- The team working together in the classroom.

regulations and weight-balance issues would render the proposal near impossible to implement. Upon a suggestion from Professor Nixon, the team investigated implementation of the technology onto UAS. After investigating the aerodynamics of a quadcopter, the team concluded that the additions could be implemented without greatly affecting the balance of the UAS. Aerodynamics would have to be considered and were addressed later within the design, with regards to the placement of the added system and carbon collection tanks. All teams researched UAS technology, carbon capture systems, and FAA guidelines and regulations for initial literature reviews. It was found that UAS must abide by certain FAA regulations that vary upon whether the UAS is flown for business or recreation and whether the weight of the UAS is over or under 55 pounds [14] [15]. For the use of UAS in a large commercial industry, a certificate of exemption from the FAA must be acquired. Only with that certificate can a UAS be flown on such a large commercial scale [16]. While there are multiple FAA regulations that must still be satisfied, implementing this system on a UAS was found to be a much more realistic and potentially attainable option in comparison to airplanes, especially when considering the number of UAS out there, and the possibility of an exponential increase in the coming years.

When finalizing a design for a next-generation UAS with the proposed technology, the team consulted with engineering professors within Binghamton University- State University of New York. The placement of the electro-swing cells had already been determined, but the placement of the carbon capture tanks was still being debated. Project Lead Zachary Sloan and design team member Brian Flynn first met with Dr. Michael Elmore, who worked with Lockheed Martin for many years. Dr. Elmore suggested the team consider the amount of CO_2

Figure 3- A standard 5-lb Carbon Dioxide tank, the original choice for the capture unit [17].

that it would take to produce a UAS in the first place, and how it must be compared with the amount of CO_2 the proposed system would capture. Dr. Elmore also directed the team towards Professor Koenraad Gieskes to discuss the possible implementation of carbon tanks. Professor Gieskes reasoned that it would be inefficient to implement a large tank on a UAS, what the team was originally considering for the design (as seen in Figure 3), because the relationship between the flight time of a UAS and the amount of CO_2 collected would not justify the large size, in regard to its weight. He recommended using propellant tanks that are commonly found in whipped cream canisters, called whipped-cream chargers. A few of these tanks would enable a UAS to collect a proportional amount of CO_2 to its flight time. With this information, the team performed a small demonstration using a UAS and model carbon capture technology.

By the time the report was nearing closure, the COVID-19 pandemic had begun escalating. New York Governor Andrew Cuomo ordered that all State University of New York (SUNY) campuses switch to online learning on or before March 19, 2020. Many students, including members of the project team, went home to finish their classes. This did not stop the project, however, as the team met on the online communication platforms Zoom and Discord, as can be seen in Figures 4 and 5. Before finalization of the report, the team consulted with industry experts on the feasibility of the project. Professor Staff arranged a meeting with Bob Mincer, the Manager of Strategic Assets for the Ontario County Industrial Development Agency and airport manager at Canandaigua Airport in Canandaigua, New York. Mr.

Figure 4- By late March, the team had switched to online communication.

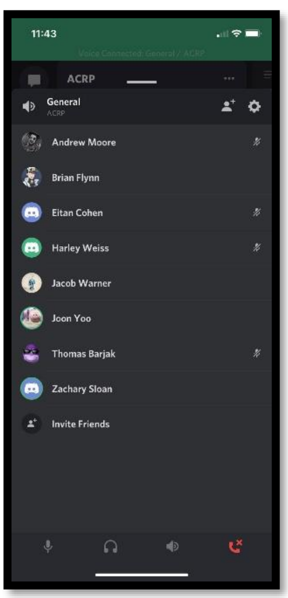

Figure 5- Discord became one of the primary means of communication because of COVID-19.

Mincer has owned and operated his own UAS for over five years and brought a unique perspective as a UAS pilot. Mr. Mincer was introduced to the proposal and shown a video of a test flight of a UAS with model carbon capture units overseen by Professor Nixon. After some questions and discussion, Mr. Mincer said he thought that the system proposed would not have a great impact on flight dynamics, as it seems lightweight, but that any electronic system added to a UAS will have an impact on its battery life. Mr. Mincer believes this will be less of a concern as technology advances.

A meeting was also conducted with Nobel-prize winning chemist Dr. M. Stanley Whittingham, as seen in Figure 6, who performs research at the Innovative Technologies Complex (ITC) at Binghamton University- State University of New York. Unlike Mr. Mincer, Dr. Whittingham was not too optimistic about advancements in battery technology. He believes that batteries won't rapidly advance in the next ten years, but that there is still a push to get the power output up from 250 Watt hours per kilogram (Wh/kg) to 500 Wh/kg. He also commented on the design of the proposed system, saying that either a pump or the UAS blades would need to be used to push the air through the cells. These two meetings solidified the information for the report.

Figure 6- Project Lead Zachary Sloan and Design Team Member Brian Flynn meet with Nobel-Prize winning chemist Dr. M. Stanley Whittingham over Zoom.

Maintenance was heavily considered within the project. Daily maintenance, such as the switching out of filled carbon tanks, will be required, with the incentive of the user being able to sell carbon to storage facilities, greenhouses, or carbonated beverage facilities. The primary maintenance, however, will be the switching out of components as both carbon capture and UAS technology improve, to improve the collection of carbon emissions. As UAS and carbon capture technologies advance, it only makes sense that they are combined to work together to a greater effect. If the proposed system is implemented, it could provide a way to remove carbon dioxide from the atmosphere and reduce greenhouse gases. Developing clean and efficient technologies in today's world is essential for the future and wellbeing of our environment and even our survival.

IV. Safety Risk Assessment

a. FAA Goals to Ensure Safety

ACRP Report 131: *A Guidebook for Safety Risk Management for Airports* defines risk as "the composite of predicted severity and likelihood of the potential outcome of a hazard," and safety as the absence of risk. To ensure the utmost safety of any system, risk mitigation is an absolute necessity. Through the ACRP, the FAA has documented many incidents and instituted regulations that reduce the chances of further problems, all to ensure safety within the US aviation system [18].

b. Safety/Risk Matrix

A risk matrix is used to analyze potential risks of a system. The FAA recommends a 5x5 risk matrix, as seen in Figure 7, that compares the severity of a potential hazard to the likelihood of said hazard occurring. Three colors identify the different levels of risk, with red, yellow, and green indicating high-level, medium-level, and low-level risks, respectively. Proposals with high-level risks cannot move forward unless the risk is lowered. Medium-level

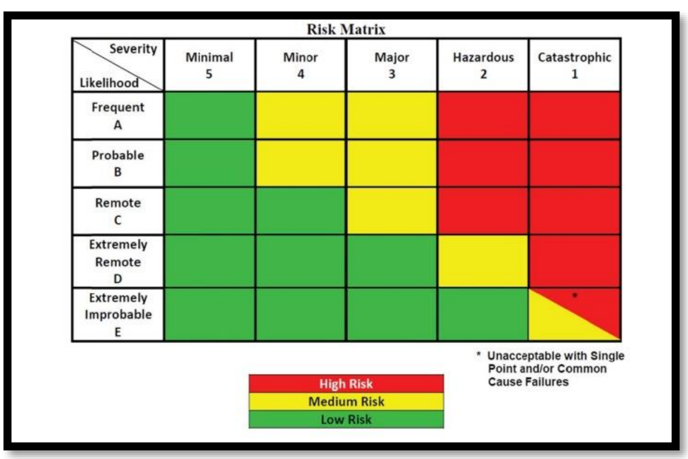

Figure 7- The FAA's recommended Risk Matrix

risks are acceptable but must be tracked and further mitigated, if possible. Low-level risks are allowed with little regulation but must be documented. The risk matrix ensures that every proposal passed by the FAA is the safest it could possibly be [18]. This matrix will be used in the next section to analyze the proposed design, determine the risks, and suggest modifications to ensure safety.

c. Potential Risks and Solutions to Ensure Safety

Perhaps the largest risk resulting from UAS is the potential of a collision with other objects. A high-speed collision between a small aircraft and a standard hobbyist UAS could easily result in damage to the aircraft, as seen in Figure 8, causing a loss of control and a crash [19].

Figure 8- Demonstration of the impact of a high-speed collision of a UAS and an airplane wing [19].

In a study performed by the FAA and the Alliance for System Safety of UAS through Research Excellence (ASSURE), computer simulations supported by material and component level testing helped determine the potential risks of collision [20]. The commercial air vehicles tested included a Boeing 737 and an Airbus A320, which aggregately represent 70% of all commercial aircrafts [20]. On the UAS side, a small quadcopter and a light fixed-wing unmanned aircraft were chosen to represent likely threats to the manned aircrafts. High-speed impacts typically resulted in complete destruction of the UAS' lithium battery, but some low-speed impacts increased the risk of fire due to a shorted battery [20]. Collisions with aircraft are a high-level risk, as they have the potential to harm or kill people. In order to mitigate this risk, it is recommended that UAS be equipped with autonomous vehicle sensors, much like what driverless cars use [21], to ensure maneuverability in the event that a collision is imminent. Amazon UAS already use sensors to aid in their flights [22]. While FAA regulations severely limit the range a UAS can fly by restricting the UAS to within the eyesight of pilots [14], sensors would still aid in risk mitigation. With all of this considered, the risk of a UAS-aircraft collision would be lowered to a medium-level risk with a major severity and a remote chance. Future studies and technological advancements can further reduce this risk.

Risk of UAS collision with objects and humans on the ground is also a significant cause for concern. Amazon's UAS, for instance, may travel faster than 50 mph and carry a payload of up to five lbs. [22]. According to the study by ASSURE, "Applications with mission profiles that have high velocities present the most risk for face and torso injury" [20]. The same study also determined that the construction of the UAS was one of the largest factors in the severity of injuries. While some UAS broke apart to absorb impact, rigid vehicles were far more likely to cause serious injuries [20]. Amazon's UAS consider this concept and intentionally self-destruct during a collision [23].

The carbon capture system proposed requires the addition of electrochemical cells and carbon dioxide storage tanks to a UAS. In a hard crash, the lithium ion flight batteries are likely to catch fire, but the carbon capture cells, which are made of heat-resistant [24] carbon nanotubes [10], will not combust. Thus, even if the battery catches fire, the addition of this system will not increase the overall intensity of a fire [24]. Therefore, the capture cells should not impose additional risk on the UAS operation, and the potential of a fire from the addition of this system is an extremely low-level risk with an extremely improbable likelihood and a minor severity. Alternatively, the carbon capture tank itself may pose a threat to other objects in collisions. The potential of the tank bursting due to impact or heat from other components was investigated. There is minimal-to-no evidence suggesting that either of these scenarios are possible, making it an extremely improbable likelihood. However, the tank will add weight and density to the UAS. Unlike many other components of the UAS, the carbon-capture tank will be rigid and remain as one piece during an impact. This increases the risk of blunt-force trauma in the event of a UAS-human collision and raises the risk to a medium-level risk with a major severity, but a remote likelihood.

A multitude of design strategies can be employed to mitigate the risk of injury resulting from carbon capture tanks. For one, the overall structure of the UAS should not be rigid, as stated earlier. When a crashing UAS fragments upon collision, much of the force is dissipated to the side, but a tough and rigid UAS that holds its shape can cause serious injury [20]. This situation can be compared to a car crash- the safest cars have large crumple zones to absorb impact and allow the passenger cabin to decelerate more gently [25]. Hazardous and sensitive components, such as the flight battery, could be stored in a protective container, while the other components should be designed to absorb and redirect the impact. When incorporating the carbon capture tanks into the UAS, the tanks should be placed low and center. Placement in any other area would create extra torque that would change the balance of the UAS and cause it to tip. With the tanks low and centered, there is room for other components to dissipate some of the impact in a collision, lowering the risk to a low-level risk with major severity but an extremely remote likelihood.

One side effect of collecting carbon dioxide with a UAS is that the mass of the UAS will increase with the amount of carbon collected. In order to mitigate the dangers of increasing the mass of a UAS, the carbon collection system will be able to shut itself off once the maximum amount of carbon has been collected. A pressure gauge will relay data back to the operator based on how full the tank is if an automatic shutdown fails so the pilot can perform a manual shutdown.

With the system only operating until the tanks are full, no more power than necessary is directed towards the collection system. This lowers the risk of increasing the weight of a UAS from a medium-level risk with minor severity and a probable likelihood to a low-level risk with minor severity and a remote likelihood.

d. Conclusion

Ultimately, the carbon capture system does not modify the way that a UAS fundamentally operates, although this is not to say that it comes without risk. Provided that important design factors such as weight distribution of new parts are considered, the carbon capture system does not greatly increase the probability of an accident. The main concern is the implications of the carbon capture system on accidents that would have occurred otherwise. While carbon capture tanks pose the greatest risk of injury, feasible design concepts have been proposed to dampen this risk. Overall, carbon capture technology can be combined with UAS technology without significant impact to safety.

V. Technical Aspects Addressed

UAS usage is growing exponentially in a wide variety of areas within the aviation field. These areas include recreational, commercial, and military usage. The number of UAS (many of which are quadcopters) that are used by companies and recreational flyers will only continue to rise rapidly. Companies such as Amazon have stated goals to utilize UAS to deliver goods directly to the consumer, rather than relying on other forms of transportation such as delivery trucks. The FAA released an aerospace forecast in 2019 which predicts that the number of registered hobbyist UAS in the United States (US) will increase from 1.2 million in 2018 to 1.4 million in 2023 [26], and the number of registered commercial UAS in the US will increase from 277,386 in 2018 to

835,211 in 2023 [26]. Given that not every UAS currently flying in the US is registered, it is likely that FAA projections are underestimates for the total number of UAS. This project proposes utilizing the great number of UAS to capture atmospheric carbon dioxide by implementing carbon capture technology onto individual UAS, resulting in a net negative carbon emission every time UAS fly.

a. The Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell

The foundation of the “Catch-CO_2: Integration of Carbon Capture Technology on UAS” project lies on a newly invented faradaic electrochemical cell created by a pair of researchers, Sahag Voskian and T. Alan Hatton from the Massachusetts Institute of Technology, who published their findings in the journal *Energy and Environmental Science* on September 30th, 2019. Their proposal is for a carbon capture cell comprised of two cathodes sandwiching a central anode. It is packaged like a fuel cell, though unlike a fuel cell, it consumes electricity. Within the individual electrodes are carbon nanotube composites. Polymerized within the anode is the compound polyvinylferrocene, a stable organometallic compound comprised of an iron cation bonded to two cyclopentadienyl rings, shown in Figure 9, which are similar in structure to benzene except with one less carbon atom and one less hydrogen atom.

The ferrocene acts as an electron source and sink, depending on the polarity of the current, which can be switched. Polymerized within the cathodes is the compound poly-1,4 anthraquinone, which serves as the agent that captures and stores carbon dioxide. A room-temperature ionic liquid

(RTIL) serves as an electrolyte, thereby permitting ions to flow between the electrodes and carbon dioxide to move into the central electrode (in this state it is an anode) for capture.

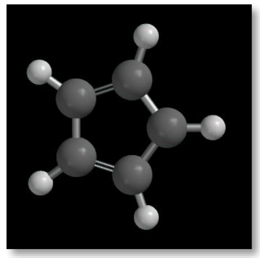

Figure 9- Ball and spoke model of a cyclopentadienyl ring [27].

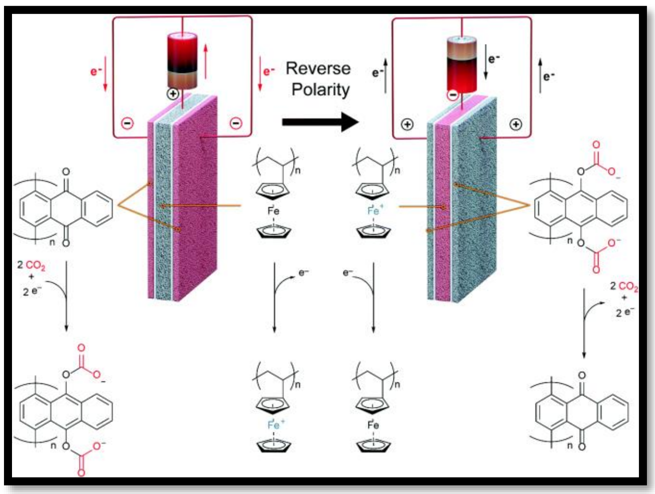

Figure 10- Diagram of Faradaic electro-swing reactive adsorption electrochemical cell and the chemical reactions it performs from the original article [10].

The method of carbon dioxide capture is as follows: electricity flows from an external power source through all three electrodes. They are wired such that the inner electrode is always the opposite polarity of the outer electrodes; the polarity of the electrodes can be reversed simply by reversing the direction of the current (shown in Figure 10). When the outer electrodes serve as anodes, electricity catalyzes a carboxylation reaction of 2 carbon dioxide molecules into a carboxyl acid for every 1,4-anthraquinone molecule. The iron in the polyvinylferrocene molecules serves as a source of electrons since they ionize into iron (I) cations. From here, the polarity of the cells can simply be reversed to decompose the carboxylic acid and release the carbon dioxide into the inner electrode, which is now the anode, for capture. The design allows for the formation of parallel gas channels since the cells can be stacked on top of each other. Specific dimensions of the cells were not listed; however, the carbon fiber mat electrode for the external/polyanthraquinone electrodes has a reported thickness of a mere 150 micrometers (μm) [10]. The Faradaic Electro-Swing Adsorption Electrochemical Cell has proven itself in the lab, operating for over 7,000 testing cycles at 90% efficiency with 60-70% quinone utilization at carbon dioxide concentrations as low as 6000 ppm while consuming minimal electricity in the process at 90 kilojoules per mole (kJ mol^{-1}) when 100% of the mat electrodes and quinones are used [10]. This still does not necessarily mean the technology may be ready for deployment since the current average atmospheric carbon dioxide concentration is more than 400 ppm or approximately 6.667% of the lowest concentration (6,000 ppm) the device has been tested at [28]. Further complicating the situation is that the reduced form of poly-1,4-anthraquinone is highly unstable in the presence of gas mixtures containing oxygen, such as air, thereby rendering it unusable to capture carbon dioxide, since it could be released back into the atmosphere before it can be contained. This proof of concept will require additional research to mitigate or eliminate these issues, as it was stated in the paper that the efficiency and technology of the cell would improve with techniques like mass production. Furthermore, even if a different, better carbon capture method is used in place of the Faradaic Electro-Swing cells, the fact that carbon capture technology is working on such a small scale proves that the technology does, indeed, exist at small enough sizes for UAS.

b. Unmanned Aircraft Systems

Commercially available UAS, colloquially known as ‘drones’, ‘quadcopters’, and ‘octocopters’, have seen rapid development within the last 15 years thanks to the miniaturization of computer systems and subsequent automation of UAS. This allows anyone with minimal training to fly a UAS since the onboard computer system can correct for user oversights or errors with flight trajectory or weather. UAS have also become stable platforms for recording images and videos with the addition of accelerometers, gyroscopes, and stabilized camera mounts which can hold bulky Digital Single Lens Reflect (DSLR) cameras, allowing them to be used by researchers, photographers, videographers, and journalists. An offshoot of quadcopters has been octocopters, which have been extensively used by filmmakers and farmers due to their superior stability, reliability and larger carrying capacity. This allows them to carry heavier video cameras and sensors compared to the smaller quadcopters. Current developments in commercial UAS are concentrated on the delivery of packages. The first company to propose commercial UAS delivery was Amazon Inc. with its CEO, Jeff Bezos, announcing ‘Amazon Prime Air’ on December 1, 2013 [29]. An example of an Amazon UAS can be seen in Figure 11. Since then, other companies such as Alphabet and UPS have begun developing UAS for use in delivery, with the promise of rapid delivery times and a reduction of carbon emissions by the elimination of delivery trucks for final kilometer delivery, as seen in Figure 12. To convince communities and regulators to approve pilot

Figure 11- Example of Amazon Prime Air UAS used for delivery. Carbon capture technology would be implemented on UAS such as the one in the example above

programs of UAS delivery systems, several companies such as Matternet, Zipline, and Swoop Aero have begun operations as medicine and/or blood delivery services in both developed and developing countries to improve their medical infrastructure [30].

Figure 12- Shown above is another commercial use of UAS, which is UPS using a UAS to complete a delivery of a package. The UAS serves as a supplement, rather than a replacement, to a standard delivery truck [32].

c. Implementation of the Electrochemical Cells on Quadcopters

Currently, the only viable method of safely mounting the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell is to utilize the existing camera mount available on some, but not all, commercially available quadcopters. Consequently, the final design cannot exceed the carrying capacity of an average quadcopter, unless several sizes of cells for different sizes of quadcopters and octocopters are to be designed.

Alternatively, the electrochemical cells could be implemented directly into the airframe of the next generation of UAS. Given that the FAA has allowed for greater design flexibility for commercial UAS compared to commercial jet-engine transport aircraft, this solution would have a greater chance of production compared to implementing and/or retrofitting the electrochemical cells into the skin of commercial jet transport aircraft. The only major consequence of this solution would be that manufacturers would have to redesign their UAS to accommodate the increase in mass and the alterations to the airframe. Thus, except for the camera mount, this solution could not be retrofitted to existing UAS. The advantage of this solution, however, is that the UAS maintains its existing functionality without a major redesign since the camera mount is left alone. Additionally, large fleets of quadcopters and octocopters have yet to be constructed by private logistics companies. Only small-scale fleets, consisting of the delivery UAS like the one shown in Figure 13, exist. Thus, a native solution that preserves the original functionality of UAS in development would be preferable for these logistics companies attempting to construct fleets of quadcopters and octocopters. Once the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells have been implemented into near-future quadcopter and octocopter designs, as shown in Figure 14, the next step is determining how best to store the carbon dioxide within the UAS. The central electrode of the electrochemical cells can be connected by a pipe to a carbon dioxide containment tank. This tank can then be exchanged between flights, allowing the UAS to continuously collect carbon dioxide while in the air. This containment tank, located low and central within the UAS, could be exchanged by mail for individuals owning UAS, similar to how SodaStream manages exchanges of its users' carbon dioxide tanks for the use in carbonating tap water [34]. For logistics fleet UAS operators, the tanks are installed inside the UAS before loading a package into the UAS for a delivery flight. From there, the UAS will complete its delivery and the collection tank will collect sequestered carbon dioxide. Once the UAS completes its delivery and returns to its base, the

Figure 13- An exemplar Amazon Prime Air UAS used as a base for integrating the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells onto a UAS [33].

logistics fleet operators can then remove full tanks of carbon dioxide and replace them with empty tanks as needed. The same process can also be used for recreational UAS without the delivery step.

Another issue that needs to be overcome once the electrochemical cells have been

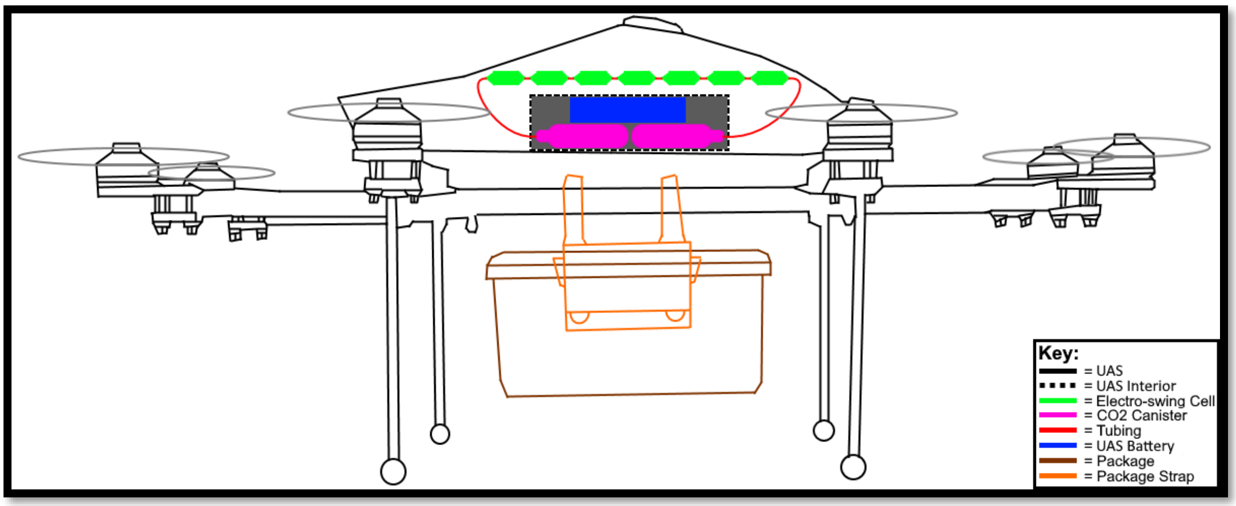

Figure 14- Schematic of an Amazon Prime Air UAS modified with the inclusion of Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells and CO2 tanks; this is a potential design for a next-generation UAS [33]; air currents created by the blades of the UAS or an air pump are two possible methods for funneling in CO_2.

implemented is power consumption. Although more efficient than existing solutions, the cells still consume significant amounts of energy. They consume between 43-90 KJ/mol of carbon dioxide extracted from the air depending on the percent quinone utilization (60% and 90% utilization respectively) [10]. Additional electrical capacity is needed to compensate for the electricity consumption of the electrochemical cells and to ensure that the utility of the UAS is preserved. This would require either additional batteries or higher capacity batteries. Given that aircraft should ideally be as light as possible, a more energy-dense battery is preferable, assuming it provides a longer flight time with an equivalent mass to existing lithium-ion batteries used in portable consumer and professional electronic devices. Existing lithium-ion polymer batteries have a maximum specific energy capacity of approximately 0.3 kilowatt-hours per kilogram (kWh/kg), which is insufficient for carbon capture [35]. Lithium-Sulfur Batteries and Lithium-Air batteries are currently in development with anticipated commercial densities of 0.65 kWh/kg, and 1.00 kWh/kg respectively [35]. This indicates that the next generation of UAS can expect their range and/or carrying capacity to increase without increasing their mass and their ability to efficiently capture carbon dioxide to improve.

Originally, we had proposed using a small high-pressure carbon dioxide tank to store the carbon dioxide after capture; however, after discussing with Assistant Director of the Engineering Design Division (EDD) at Binghamton University- State University of New York Professor Koen Gieskes, we settled on a smaller tank the size of whipped-cream chargers. This is because the short flight duration of a UAS would not allow for significant enough carbon capture to fill the larger tank that was being considered but would allow for enough carbon to fill a smaller tank. A whipped-cream charger is approximately 1.8 centimeters (cm) in diameter and 6.3 cm tall with a volume of about 10 cm^3 [36].

The process for carbon collection is as follows- the carbon dioxide collected from the individual capture cells will converge into a single flexible rubber tube. This tube connects to the removable carbon dioxide storage tank with a built-in pressure gauge to determine the remaining capacity left in the tank. The carbon dioxide storage tank is then filled, similar to how a portable oxygen tank is used by medical staff to treat respiratory distress. A removable tank is a simpler and lighter solution compared to using a permanent tank and a release valve to extract captured carbon dioxide. Once the UAS has completed its delivery or deliveries, it will return to its base, at which point a worker could replace the full carbon dioxide storage tank with an empty one and unload the carbon from the full tank to enable the tank to be used on a future flight. To avoid unnecessary checks of the tanks, the carbon dioxide storage tank pressure would be relayed to the pilot along with other mission-critical information such as speed, heading, altitude, GPS coordinates, and current weather conditions.

The advantage of this design is that it can be easily applied to both existing and developing UAS. In the case of existing UAS, a camera mount adaptor could be used to safely and securely mount the carbon dioxide collection system to a hobbyist UAS so long as its owner did not mind losing the ability to use their UAS as an aerial photography platform. Alternatively, the carbon dioxide collection system could be mounted on the top of the UAS if an appropriate adaptor was created. However, this would require significant physical and/or software modification of the UAS due to the additional torque acting on the UAS that could cause it to lose control and fall out of the sky. Either way, the primary concern would be determining how the carbon dioxide collection system would receive electricity, since cameras are normally battery-powered and hence do not require an external power source for sustained usage.

Although the issue of power supply could be alleviated with the addition of a rechargeable battery to the carbon dioxide collection system, this would not be ideal since this may introduce thermal issues. It is not clear what the thermal tolerances are for the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells, other than the fact that carbon nanotubes have high heat resistance. A more ideal solution would be to have the carbon dioxide collection system powered externally by the UAS itself; however, this has its own set of issues. First, this would reduce the probability that a user would retrofit their UAS since it would have to be modified to include an external electrical harness. Once this harness was installed, there are still the issues of the UAS getting caught on objects that otherwise would have missed such as tree branches or birds, and that the addition of a cavity to the exterior of the UAS increases its vulnerability to precipitation if it is not properly sealed water-tight or it gradually loses its water-tight seal with wear and tear. Thankfully, these issues are not present if UAS currently in development are considered for modification. In this case, the carbon dioxide tank can simply be mounted in the interior of the UAS with an access opening to extract the tank, as explained above, or the tank could be mounted externally using a similar locking mechanism as the battery package available on certain UAS. The electrochemical cells, meanwhile, can simply be mounted onto the skin of the UAS and connected internally into a single pipe as before to the carbon dioxide storage tank. All of this must be packaged low and towards the center of the UAS, preventing added torque from acting on the UAS, which is not possible with all retrofits. Regardless, there would be a reduction in flight time that would result from the additional load on the rechargeable battery in the UAS. Since battery energy densities are expected to improve with time as new technologies enter the market such as Lithium-Sulfur batteries, this should become less of an issue in due time.

d. Testing the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells on Quadcopters

With the help of Professor Nixon and Professor Staff, the team was able to test a model of the full carbon capture system on a DJI® Inspire 2 UAS, a commercial UAS intended for filmmakers. The model consisted of a carbon capture tank and a pair of Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells and were fabricated via a 3D printer located at the Emerging Technologies Studio (ETS) on campus at Binghamton University– State University of New York. The model tank was 9.65 cm high with a diameter of 2.87 cm. The model capture cells were 9.5 cm long, with a maximum width of 2.65 cm that tapered off towards the ends. The items, seen in Figure 15, were scaled down according to the size of the UAS and were lightweight to model the actual weight of the items in real life. The UAS flight, seen in Figure 16, was overseen by Professor Nixon, who noted after the flight that the system did not significantly affect the handling or performance of the UAS. Thus, it can be concluded that the basic concept of the system has been successfully tested on a UAS and could feasibly be implemented into fleets.

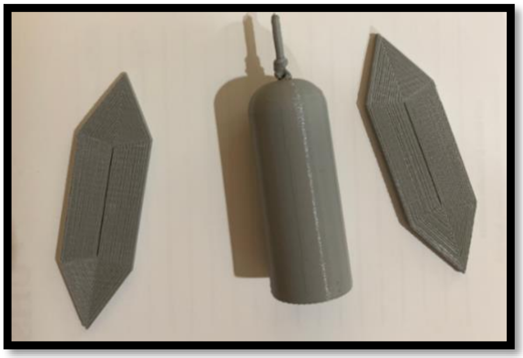

Figure 15- Photograph of a model of the complete system of Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells. All three pieces were fabricated using the 3D printers available to students at the Emerging Technology Studio (ETS) at SUNY Binghamton University.

Figure 16- Test flight of the modeled Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells on a DJI® Inspire 2.

VI. Interactions with Airport Operators and Industry Experts

Bob Mincer is the Manager of Strategic Assets for Ontario County, New York, and the Ontario County Industrial Development Agency. He has had this role since 2018. Mr. Mincer's responsibilities include management and oversight of the Canandaigua Airport (IUA) in Canandaigua, New York. He also is a licensed private pilot and experienced UAS operator. The team organized a Zoom chat with Mr. Mincer on March 31, 2020, to ask for his input.

To start off the meeting, Professor Staff introduced Mr. Mincer to the class, as seen in Figure 17. He discussed the Binghamton University Scholars Program and the class that was structured around the ACRP design competition. Project Lead Zachary Sloan then explained the concept and design that the team had come up with, as seen in Figure 18.

After listening to the proposal, Mr. Mincer asked some questions of his own to fully understand the system. Once everyone was on the same page, Project Lead Zachary Sloan asked Mr. Mincer a series of questions that had been prepared by the team. Some of the questions dealt with the feasibility of adding the system to a UAS and whether it would affect flight dynamics, while others dealt with the increasing size of the UAS industry. Mr. Mincer gave some helpful insight with his answers. He believes that the system the team proposed will not have a great impact on flight dynamics of a UAS- this was further supported by the test we had done with the mock carbon capture cells and tank. This ensured safety with the addition of this system.

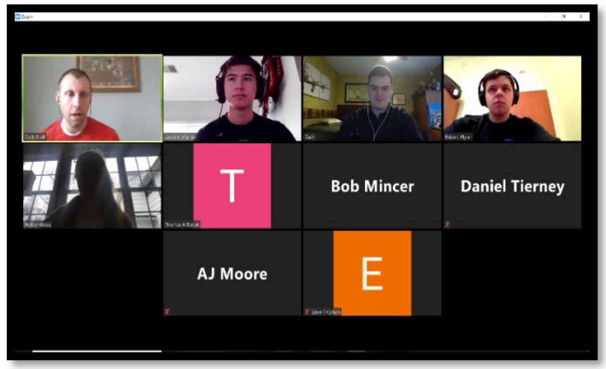

Figure 17- Screenshot of the Zoom meeting with Mr. Mincer and the Catch CO2 team.

He did, however, warn that any electronic device added to a UAS will have an impact on battery life. Mr. Mincer, when asked where he thought battery life for UAS will go as time moves on, answered that he believes maintaining battery life will not be a concern, as advancements in UAS technology will push battery expansion. At the conclusion of the meeting, Mr. Mincer encouraged the continuation of the project and wanted to know where the team would take the design next. He acknowledged the US Department of Energy's (DOE) interest in funding direct-air capture projects and noted the project's relevancy to current issues.

Figure 18- Project Lead Zachary Sloan discussing the proposal with Mr. Mincer on Zoom.

The team attempted to arrange a meeting with Lt. Colonel Brenton, a UAS expert. Lt. Colonel Brenton, although interested in the project, was unable to arrange a meeting in time for the report.

VII. Projected Impacts

a. Introduction

With additional research, it can be determined whether the faradaic cells can function in normal atmospheric conditions. Regardless, the existence of such technology supports the fact that carbon capture works on a level fit for application within this project. However, there are still costs associated with the implementation of these cells on UAS. If left unchecked, these costs will deter companies from adopting the proposed system despite their interests in improving the environment. To overcome these issues, uses for captured carbon dioxide must be developed, and tax credits can be instituted to overcome the initial cost of implementing the electrochemical cells on UAS, thereby allowing for the mass adoption of this carbon-capture technology.

b. Meeting FAA Goals

The primary FAA Goal this project seeks to address is "Sustaining our Future: To develop and operate an aviation system that reduces aviation's environmental and energy impacts to a level that does not constrain growth and is a model for sustainability" from the FAA's "Destination 2025" (seen in Figure 19) vision [8]. The relevant desired outcome of this goal, according to the FAA, is that "Aviation's carbon footprint does not become a constraint to growth" [8]. This is met with the Faradaic Electro-Swing Reaction Adsorption Electrochemical Cell. By integrating the cells into near-future UAS for hobbyists and logistics fleets, and retrofitting them to existing hobbyist UAS, carbon capture can be integrated into the current aviation system without acting as a major strain on economic growth.

Figure 19- "Destination 2025" [8].

c. Commercial Potential

To allow for maximum usability across different designs of UAS, multiple sizes of Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell retrofit systems could be developed. Multiple sizes would increase costs, however, which should be avoided since this technology is new and cutting edge. A considerably better option is to implement the technology into near future UAS. Collected carbon dioxide could be sold to industries that use carbon dioxide as a feedstock. These industries include carbonated beverage manufacturers, farmers (for usage in greenhouses), or producers of carbon-neutral petroleum products. Additionally, the extracted carbon-dioxide could be sold to fossil fuel companies who use carbon dioxide to aid in the extraction of petroleum. This option is carbon-positive, however, since more carbon dioxide is pumped into the air from the extraction of petroleum than carbon dioxide that is extracted from the air and is thus not recommended. These options would reduce the carbon impact of most industries, as they wouldn't need to rely on fossil fuels to generate carbon dioxide; rather, they would purchase collected carbon from this implemented system, essentially creating a recycling system for CO_2 and stifling extra production. This would also be profitable once scaled up to the projected UAS fleets that logistics companies desire since carbon dioxide has an estimated value of $50-$100 per metric tonne for the Faradaic Electro-Swing Reactive Adsorption Cell [10].

d. Process of Implementation

For potential retrofits of existing UAS, an FAA re-certification process would be required for the UAS and its retrofit kit to ensure that a retrofit does not compromise the flight dynamics of the UAS. If this were to happen, there is the possibility that the UAS would be unable to safely complete its mission, or worse, fall out of the sky during a mission. Regardless of whether the carbon dioxide capturing UAS used by potential future fleet operators such as Amazon, Alphabet, or UPS are retrofitted with the technology or come with it by default, they will be inherently more cost-prohibitive compared to their non-carbon-dioxide- capturing counterparts. To overcome this, tax incentives could be implemented by the various municipal, provincial, and national governments that prospective UAS operators may wish to operate in. This could include tax credits on installing new UAS and being able to use a tax deduction for carbon dioxide collected from current or future carbon taxes levied on businesses. This is in addition to sequestered carbon dioxide, which could be sold to industries that use carbon dioxide as a feedstock, such as carbonated beverage manufacturers or farmers for their greenhouses, as seen in Figure 20. It could also be used to produce carbon-neutral petroleum products, also seen in Figure 20 [11]. This would reduce these industries' reliance on fossil fuels to generate the carbon dioxide they need. Additional incentives could be given to simply pump the collected carbon dioxide underground permanently, rendering it unusable for human use and unable to harm the environment. The primary caveat with this would be if the area the sequestered

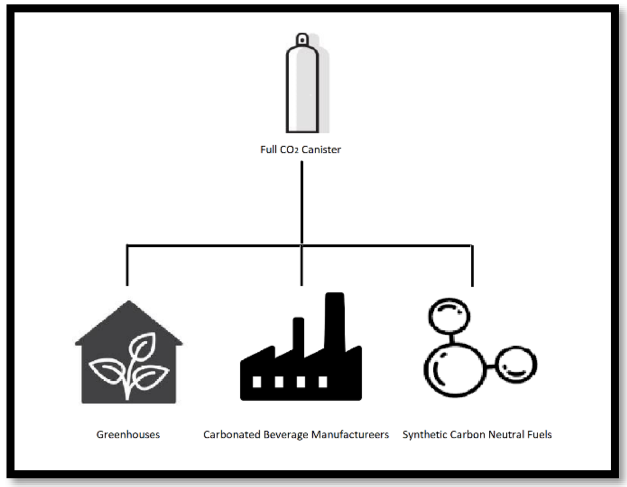

Figure 20- Diagram of potential uses for sequestered carbon dioxide captured using the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell.

carbon dioxide was injected into was disturbed either by the environment (such as in an earthquake) or by humans manipulating the land. In these cases, the sequestered carbon dioxide could escape captivity. This would be viable if the other uses for sequestered carbon dioxide were to become saturated and are no longer tenable business models. The carbon taxes could be tiered such that companies would be given more of a tax deduction/return if carbon is pumped into the ground versus sold off to industries, especially to fossil fuel companies.

e. Effects of Implementation

Currently, the FAA regulations are optimized for risk mitigation in the name of safety. A logistics company that currently wants to perform test flights of their delivery UAS service needs to obtain a Part 135 certification from the FAA, which is largely the same process used for companies starting airlines, with some exceptions, such as not requiring flight manuals onboard the UAS [37]. However, there are restrictions not seen with airlines depending on which certification a company chooses to apply for. Since the process is bureaucratic, consisting of five separate phases, it is lengthy; the process is further elongated due to an extensive application and review process conducted by the FAA on the applicant and their required documentation. Consequently, only a single company, UPS Flight Forward, Inc., has managed to secure a Standard Part 135 air carrier certificate so far. This allows them few restrictions on their operations as a UAS medical supply delivery service for WakeMed Hospital in Raleigh, North Carolina [37]. The primary restriction is that any form of expansion into a new form of operation must receive FAA approval first before it can commence. Additionally, Wing Aviation, LLC has received a Single pilot air carrier certificate, allowing them to have one pilot-in-command certificate holder and three second pilots-in-command certificate holders. However, there are restrictions included in this certification, such as aircraft size and the scope of Wing Aviation's operations [37]. This approach, which could be considered overly cautious by some, is reasonable due to the need to protect consumers from damages caused by UAS. It would be expected that these restrictions would be lifted once logistics companies have demonstrated that their fleets of UAS are reliable and economically significant. UAS logistics fleet operators would then be able to make business decisions without interference or requiring authorization from the FAA.

To reiterate, UAS delivery services need to expand to become sufficiently frequent and reliable to warrant deregulation in favor of self-regulation. Thus, companies have no choice but to expand under the current Part 135 air carrier regulations and live up to their promises of UAS package delivery if they wish for it to become as commonplace as delivery via the current last-mile delivery system. Given that logistics companies such as Amazon are focused on consistently improving their customer's experience, it would be unlikely for them to not attempt to expand under and/or advocate for changing the current FAA regulations, especially if the end goal for Amazon, UPS, and other private couriers is to eventually replace their fleet of delivery trucks with delivery UAS, and potentially even the United States Postal Service in a bid to reduce shipping costs to an absolute minimum. This would also come with the added benefit of reducing carbon emissions from delivery trucks. The carbon concentration in the atmosphere would be further limited with an increase in the number of UAS, giving incentive for companies who want to positively impact the environment to expand their UAS fleets.

f. Affordability and Utility

The Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell is feasible for entry into the market. The cells have proven themselves viable in simulated real-world conditions, being able to extract carbon dioxide from the atmosphere while also not requiring high-power consumption [10]. A tank design to store small amounts of sequestered gases exists as evidenced by whipped-cream chargers [36]. The primary hurdles remaining for the device itself are mass-production and managing waste heat. As for the implementation of the device in the industry, what remains is convincing potential customers such as Amazon, Alphabet, and UPS to use this proposed technology. This can be overcome with the use of tax incentives and the selling of sequestered carbon dioxide to industries that require it. Alternatively, a government agency or other independent third party can handle the permanent disposal of sequestered carbon dioxide if companies wish not to deal with the carbon dioxide themselves.

g. Cost Analysis

The exact cost of implementing the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cell cannot be determined currently since the original inventors, Voskian and Hatton, failed to include a cost estimate within their original paper. They only state that their system should be more efficient once it enters mass-production [10]. This is understandable, given that their invention is currently an idea, not a commercial product. Nevertheless, we can investigate the cost of electricity required to power the UAS and the electrochemical cells.

The energy required to sequester one kilogram of carbon dioxide is dependent on the time desired to sequester one kilogram (kg). Voskian and Hatton quote a range of energy values to sequester carbon dioxide from the air at 43-90 kilojoules per mole (kJ/mol) of carbon dioxide [10]. Converting this to kJ/kg by dividing by the molar mass of carbon dioxide (0.04401 kg), the energy required is 97.7-204.5 kJ/kg of carbon dioxide. If one wanted to sequester one tank's worth (~$1.96*10^{-5}$ kg) of carbon dioxide per full 30-minute flight, $1.066*10^{-6}$-$2.231*10^{-6}$ kilowatt-hours (kW/h) would be required. On the other hand, if one wanted to sequester one kg of carbon dioxide per minute of flight time, 1.628-3.408 kW/h would be required. As for the UAS itself, the specifications of the battery exemplar Amazon UAS are 10-ampere hours (A/h) and an operating voltage of 36 volts (V) [22]. Thus, the total power consumption that the UAS draws from its lithium-polymer battery is 36V*10(A/H)=360 W. Converting this into kilowatts per hour (kW/h), (.36 kW)/(.5 hours)=.72 kW/h across a full 30-minute flight. Therefore, the total range of power consumption is 0.720001-0.720020 kW/h for $1.96*10^{-5}$ kg of CO_2 per 30-minute flight. If one assumes a best-case scenario by charging the UAS fleets using exclusively onshore wind farms, as seen in Figure 3, the cost to charge each UAS carbon neutral is $0.05 per flight using an average cost of $0.0736 per kW/h [38]. Using photovoltaic cells, also seen in Figure 21, is not dramatically more expensive at $0.09 per flight with an average cost of $0.1253 per kW/h [38]. Multiplying this expected electricity cost across the expected commercial fleet of UAS nationally of 835,211 by 2023 [18], and the expected electricity usage for one flight of the entire fleet is $61,471.53- $75,349.40. Additionally, multiplying the expected commercial UAS fleet (835,211) by the amount of carbon dioxide captured per 30-minute flight ($1.96*10^{-5}$ kg), the expected quantity of carbon dioxide sequestered by the commercial UAS fleet is 16.3701 kg per flight.

Figure 21- To minimize carbon emissions from charging the UAS, renewable resource plants like onshore wind farms [39] and solar plants [40] can be used.

While this may seem expensive, it really is not when compared to the cost of flying the fleet without the carbon capture technology, as this projection accounts for both the cost of flying the fleet and capturing the carbon. Since companies and operators will be flying anyway, and the strain on the UAS battery from an added system will lessen as technologies advance, the added cost of capturing carbon will decrease, and the carbon will most likely yield a profit after some time. This is in addition to incentives given to companies that turn to environmentally friendly technology. These calculations also do not account for the additional mass required for the tanks to store sequestered carbon dioxide, nor the sequestered carbon dioxide itself. In fact, there is exponential mass gain since, to sequester more carbon dioxide, more tanks are required. Eventually, much like with lithium-polymer batteries, there will be an upper limit to how much carbon dioxide is collected before the quantity sequestered becomes unsustainable for the UAS due to being unable to safely and efficiently complete its mission.

There is still developmental potential for the electro-swing cells since further research and development is required for it to become commercially viable. This is unlike lithium polymer batteries, which, according to Binghamton University- State University of New York professor and Nobel Prize Laureate Dr. M. Stanley Whittingham, are not expected to have significant developments in the next decade. The goal for lithium-polymer batteries is to double the current maximum battery energy density from 250-Wh/kg to 500 Wh/kg. Additionally, he stated that it would be necessary to include air ducts to siphon air into the Faradaic Electro-Swing Reactive Adsorption Electrochemical Cells due to the intrinsically high energy requirements to sequester carbon dioxide in any form of direct-air-capture system. It is only possible to estimate the power consumption and the mass of carbon dioxide sequestered due to the lack of information regarding the projected cost to generate electricity or the expected number of commercial UAS to be in service over the next 10-20 years. The FAA and the US Energy Information Administration (EIA) both end their predictions in the year 2023 [5] [38]. Nevertheless, it can be safely concluded that the cost of renewable electricity should continue to decrease and the total number of UAS in service should continue to increase as technology improves. The number of flights an individual UAS will make over a set amount of time simply cannot be predicted at this time due to the number of factors at play such as regulations and technology that affect the rate of expansion of UAS delivery services.

VIII. Summary and Conclusion

The implementation of a UAS-based carbon collection system is highly advantageous. There is room for great improvement in the environmental impact of the aviation industry, and the proposed system can help realize that potential. The existence of the faradaic electro swing cell has proven the feasibility of miniaturized carbon capture technology. When combined with UAS, which predominately operate on electric batteries, the proposed system will have the ability to operate as a carbon neutral or even carbon-negative device. Considering how the concentration of carbon dioxide in the atmosphere will grow exponentially in the next few years, a solution such as the one proposed is integral and even necessary for maintaining the atmosphere and our very existence.

The UAS market is still an emerging industry that will continue to improve drastically. If companies such as Amazon follow through with their promise of utilizing UAS on a large scale, they will undoubtedly need to improve the technology to fulfill their goals. With improved UAS comes an increase in carbon collection if this system is already integrated. Even if it is only feasible to place this technology on the highest end UAS today, the rest of the market will likely grow in this direction, allowing easier integration and marketability. Likewise, carbon capture technology has come a long way and will only continue to grow. From massive direct-air capture plants to miniaturized pressure-swing, temperature-swing, and now electro-swing cells, scientists across the globe have been pushed to create new technologies and find innovative solutions to this impending problem. It only makes sense to utilize what they have given us to try and mitigate the amount of carbon in our atmosphere and contribute to a better airspace for the future.

Appendix A: List of Complete Contact Information

Students:

Thomas Barjak
tbarjak1@binghamton.edu

Eitan Cohen
ecohen49@binghamton.edu

Brian Flynn
bflynn2@binghamton.edu

AJ Moore
amoore20@binghamton.edu

Zachary Sloan
zsloan1@binghamton.edu

Daniel Tierney
dtierne2@binghamton.edu

Jacob Warner
jwarne12@binghamton.edu

Harley Weiss
hweiss5@binghamton.edu

Joonhwan Yoo
jyoo45@binghamton.edu

University Advisors:

Chad Nixon
Adjunct Professor-Binghamton University Scholars Program
Binghamton University
State University of New York Binghamton

Zachary Staff
Adjunct Professor-Binghamton University Scholars Program
Binghamton University
State University of New York Binghamton

Non-University Partners:

Bob Mincer
Manager of Strategic Assets
Ontario County IDA

Appendix B. Description of Binghamton University

Binghamton University, as seen in Figure 22, is a premier public university with campuses in Binghamton, Vestal, and Johnson City, New York. It was originally founded in 1946 as Triple Cities College, a branch of Syracuse University, with the intention of educating local veterans who fought in World War II. The name later changed to Harpur College in 1950 to honor Robert Harpur, a teacher and patriot. It was not until 15 years later that the campus was formally incorporated into the SUNY System as the State University of New York at Binghamton [41]. Currently, the university consists of six individual colleges: the Harpur College of Arts and Sciences, the College of Community and Public Affairs, the School of Management, the Decker College of Nursing and Health Sciences, the Thomas J. Watson School of Engineering and Applied Science, and the School of Pharmacy and Pharmaceutical Sciences [43]. As of 2019, Binghamton University had a 42.5% acceptance rate, and students averaged a GPA of 3.65 with an average ACT score of 31 [44]. The student body population currently consists of 14,021 undergraduates and 3,747 graduate students, with many participating in the over 160 clubs that the university offers. The university also participates in Division I athletics.

Figure 22- Campus at Binghamton University [42]

In a 2020 *Forbes* ranking, Binghamton University was placed at number 39 in the list of top national public universities. The university also occupies the number 39 spot on *Forbes*

"America's Best Value College" [45]. *U.S. News* places Binghamton at number 120 in the ranking of best undergraduate engineering programs [46].

Appendix C. Description of Non-University Partners

a. Canandaigua Airport (Bob Mincer)

Bob Mincer is the Manager of Strategic Assets for Ontario County, New York, which is a role he has had since 2018. Mr. Mincer manages and oversees the Canandaigua Airport (IUA) in Canandaigua, New York. Mr. Mincer is a licensed private pilot and an experienced UAS operator; he has been piloting his own private UAS for five years. Most of his time flying the UAS is spent using the mounted camera to record footage of the sights below. Occasionally, he will use the UAS to assist in algae removal from the local lake.

Mr. Mincer met with the team on March 31st, 2020 on the online conferencing system Zoom due to the COVID-19 pandemic and the enforcement of social distancing policies. Despite this, a lot was gained from this meeting, as Mr. Mincer was able to give valuable input from his experience as a UAS pilot and insight into how any additional system would affect the UAS, not through its flight dynamics but rather the consumption of power.

Appendix E. Evaluation of the Educational Experience

a. Student Response

1. Did the ACRP Design Competition provide a meaningful learning experience for you? Why or why not?

The ACRP Design Competition has certainly provided a meaningful learning experience for the team. Students unanimously agreed that the competition has encouraged all individuals to perform research in a new field, learn about how aviation interacts with other communities and impacts the environment, and understand the perspective of the aviation industry on these issues. Students also gained valuable skills that will improve their efficiency in future collaborative projects beyond the context of aviation. It is evident that the division of the larger team into smaller subgroups was a new experience for many. Students learned about communication in a large group where everyone has a different area of specialty. Each subgroup reported on a different aspect of the project, so synthesis and communication skills were integral to the outcome of the project. For some members, this was their first time reading and writing reports to contribute to a group. Every member was able to take away a new experience from this project, whether it was collaboration in a large team or research within a field they had not previously considered.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

Initially, the team had only minimal knowledge regarding aviation. The original plan was intended to reduce the environmental impact of airplanes, targeting carbon emissions. It was difficult to form an agreement upon the best way to reduce carbon emissions. Some teams explored fuel alternatives, electric aircraft, and carbon capture. Ultimately, the team settled on a method of carbon capture involving adsorption, which led to more difficulty. Since the team originally lacked knowledge in aviation, there was much debate over the ideal way to deploy such technology. Retrofitting existing planes, incorporating into new aircraft, and applying to the rapidly growing UAS industry were all proposed. Eventually, team efforts resulted in an understanding of rules and regulations. It became clear to everyone that application of carbon capture technology to the UAS industry was the best way to proceed.

Logistically speaking, communication was a key difficulty. Prior to the COVID-19 pandemic, participants frequently had full or overloaded schedules, so it was not easy for some of the subgroups to meet outside of regularly scheduled class time. The team established multiple group chats, as well as a Discord server, in order to facilitate collaboration even when the teams were unable to meet. Later, New York State Governor Andrew Cuomo mandated that all universities in the SUNY system (including Binghamton University) migrate to online instruction formats due to the severity of the COVID-19 pandemic. Many students opted to cancel on-campus housing and travel home. While the pandemic and transition to online classes caused a significant disruption, Discord's robust communication platform made it easy for both sub-teams and the full team to hold meetings, deliver announcements, and share files. Most students were highly satisfied by the decision to use Discord to facilitate online meetings.

3. Describe the process you or your team used for developing your hypothesis.

The team started on a broad level and slowly focused the topic into a reasonable hypothesis. Every round of focusing included input from each member individually, as well as research and group response. At first, everyone proposed their ideas, making it apparent that environmental impact was important to the team. Students eventually divided into two teams, with this one agreeing to research a method of carbon capture. From there, students determined the best way to apply this technology, as well as the different challenging aspects of the project. Input from the advisors, as well as research from individual students, suggested that the topic should be narrowed down to applying a specific form of carbon capture to UAS, especially commercial fleets. There are many hobbyist UAS currently registered, but with the technology becoming more accessible and large industries making big plans, it was clear to everyone that this was a good path to take.

4. Was participation by industry in the project appropriate, meaningful, and useful? Why or why not?

Consulting with industry professionals helped the team to draw in relevant information and surface errors in design. Many students reported that there were problems and drawbacks missed in the original designs, but industry professionals helped to patch these issues. Additionally, the course advisors, Professor Chad Nixon and Professor Zachary Staff, were of constant help to the team. Both being experienced in the field, they offered insight towards what was and was not acceptable in the aviation industry. Original designs sought modifying existing aircrafts, and the advisors directed us towards relevant legislation and requirements. Some students, however, felt that the team did not consult with enough outside sources. The application of a carbon capture system to a UAS was discussed with an airport leader towards the conclusion of the research without any previous input. Another discussion with a research professor at Binghamton University was also held in the final week. These meetings concerned many students and mandated last-minute changes to some sections of the project.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

Students have gained many valuable skills for collaborating in a team-based environment in the future. The students were able to work closely with individuals from diverse backgrounds with different philosophies regarding the completion of assignments. This experience is reflective of that in the workforce. Some students indicated that their future plans included work in a team-driven environment. Other students expressed that the competition increased their appreciation for the technical side of the aviation industry, which they were not interested in previously. No one entered the competition with an abundance of aviation knowledge. For some students, this was their first research experience, covering all topics of applied research from planning to creating and evaluating a design. Overall, everyone believes that the competition provided a unique experience and opportunity to learn that will impact their success in future projects.

b. Faculty Response

1. Describe the value of the educational experience for your student(s) participating in this Competition submission.

The ACRP design competition is unique because it provides an opportunity for the students to research and solve real-world problems. This type of experience is especially important for graduate school and the workforce. The students follow their idea from the ground up, initially identifying a problem independently (rather than being given one), and then gathering as much research as they can to design and analyze a solution. Real-world experiences as such are seldom provided in academia and are rarely opportunities for first-year researchers. Meanwhile, the students are gaining valuable teamwork skills, including working with a diverse student body, trust in each other, and the importance of an individual's contributions.

2. Was the learning experience appropriate to the course level or context in which the Competition was undertaken?

Since all the involved students were first-year researchers, everyone joined the course with limited experience regarding team-based work. These students had not previously experienced such heavy time constraints and a large emphasis on communication. As so, every student was pushed to improve their communication and management skills. The group layout, which consisted of four teams and a project leader, further increased the accountability of each student individually.

3. What challenges did the students face and overcome?

As mentioned previously, this was the first team-based real-world research experience for many of the students. This type of research is not typical for first-year students to complete. It was difficult for the individual teams to find appropriate meeting time, and the level of management and independence was new to many. The students employed their own solutions to these problems, including platforms for remote collaboration like Discord and GroupMe. Most prominent, however, was the impact of the COVID-19 pandemic. Binghamton University quickly transitioned to an online learning format, which was a big shock to many classes, especially research experiences requiring peer-to-peer collaboration. Students responded by increasing use of the aforementioned collaboration platforms, with the addition of Zoom. While the transition was foreign territory for many, the teams were quick to adapt and continued to collaborate on assignments.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

The ACRP design competition is highly recommended as an educational utility. The participating students are taught critical skills regarding communication, collaboration, management, and responsibility. The experience is greatly different from a traditional classroom environment, and the skills gained directly impact workforce readiness. Furthermore, students develop a knowledge of and appreciation for the aviation industry. For students who plan to work in such an area, this experience is very important and directly related to workplace success.

5. Are there any changes to the Competition that you would suggest for future years?

The ACRP Design Competition has included relevant categories for many years, and recently they have expanded. These expansions help the competition to remain both interesting and relevant. In the future, revisions and the additions of new categories should continue. Furthermore, the role of the competition could be amplified so ACRP can include a research and development pipeline. While some of the proposals are hard to develop, many of them have the potential to impact the aviation industry and could be advanced to the prototype level.

Appendix F. Reference List in Full

[1] DAWE. “Observed Changes in Our Climate System.” Environment.gov.au. [Online]. Available: https://www.environment.gov.au/climate-change/climate-science-data/climate-science/understanding-climate-change/indicators. [Accessed Mar. 3, 2020]

[2] Air Transport Action Group. “Facts & Figures.” Atag.org. [Online]. Available: https://www.atag.org/facts-figures.html. [Accessed Feb. 17, 2020]

[3] R. Moore, *et al.*, "Biofuel blending reduces particle emissions from aircraft engines at cruise conditions,” Nature, Mar. 16, 2017. [Online]. Available: https://www.nature.com/articles/nature21420.

[4] M. Kousoulidou and L. Lonza, “Biofuels in aviation: Fuel demand and CO_2 emissions evolution in Europe toward 2030,” in *Science Direct*, Apr. 9, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920915300092

[5] Federal Aviation Administration. “UAS by the Numbers.” FAA.gov. [Online]. Available: https://www.faa.gov/uas/resources/by_the_numbers/ [Accessed Feb. 17, 2020]

[6] UPS. “UPS Flight Forward Attains FAA’s First Full Approval For Drone Airline.” Pressroom.ups.com. [Online]. Available: https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1569933965476-404 [Accessed Mar. 19, 2020]

[7] Amazon. “Prime Air Fast Delivery.” Amazon.com [Online]. Available: https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011 [Accessed Mar. 19, 2020]

[8] Federal Aviation Administration, “Destination 2025,” *Federal Aviation Administration*, 25-Aug-2011. [Online]. Available: https://www.faa.gov/about/plans_reports/media/Destination2025.pdf. [Accessed: 12-Feb-2020].

[9] “Commercial Market Outlook 2019-2039,” *Boeing*. [Online]. Available: https://www.boeing.com/resources/boeingdotcom/commercial/market/commercial-market-outlook/assets/downloads/cmo-sept-2019-report-final.pdf. [Accessed 27 Feb. 2020].

[10] S. Voskian and T. A. Hatton, “Faradaic electro-swing reactive adsorption for CO2 capture,” *Energy & Environmental Science*, vol. 12, no. 12, pp. 3530–3547, Oct. 2019, doi: 10.1039/C9EE02412C

[11] “Engineers develop a new way to remove carbon dioxide from air,” *ScienceDaily*, 25-Oct-2019. [Online]. Available: https://www.sciencedaily.com/releases/2019/10/191025170815.htm. [Accessed: 12-Mar-2020].

[12] Amazon, Cambridgeshire, U.K. Amazon Prime Air. Accessed: Feb. 27, 2020. [Online Video]. Available: https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011. [Accessed: 11-Feb-2020].

[13] "Recreational Flyers & Modeler Community-Based Organizations," *FAA*, 06-Dec-2019. [Online]. Available: https://www.faa.gov/uas/recreational_fliers/. [Accessed: 11-Feb-2020].

[14] (2016). Federal Aviation Administration, "SUMMARY OF SMALL UNMANNED AIRCRAFT RULE (PART 107)," *FAA News* [Online]. Available: https://www.faa.gov/uas/media/Part_107_Summary.pdf. [Accessed 12-Feb-2020].

[15] (2018). "Text - H.R.302 - 115th Congress (2017-2018): FAA Reauthorization Act of 2018," *Congress.gov* [Online]. Available: https://www.congress.gov/bill/115th-congress/house-bill/302/text?q={"search":["hr+302"]}&r=1. [Accessed: 12-Feb-2020].

[16] (2014). Federal Aviation Administration, "Public Guidance for Petitions for Exemption Filed under Section 333," *Faa.gov* [Online]. Available: https://www.faa.gov/uas/advanced_operations/section_333/how_to_file_a_petition/media/section333_public_guidance.pdf. [Accessed: 12-Feb-2020].

[17] "5 lb Aluminum CO2 Air Tank." Amazon. https://www.amazon.com/Aluminum-CO2-Air-Tank/dp/B000EXWIVM (accessed April 2, 2020).

[18] K. Neubauer, D. Fleet and M. Ayres Jr., "ACRP Report 131: A Guidebook for Safety Risk Management for Airports," *ACRP*, 2015. [Online]. Available: https://static1.squarespace.com/static/59023408197aea7f140106fe/t/5908c81017bffc90f0de8a95/1493747745904/SRM+for+Airports.pdf. [Accessed 15-April-2020].

[19] P. Gregg, "Risk in the Sky?," *University of Dayton, Ohio*, 13-Sep-2018. [Online]. Available: https://udayton.edu/udri/news/18-09-13-risk-in-the-sky.php. [Accessed: 10-Mar-2020].

[20] "FAA and ASSURE Announce Results of Air-to-Air Collision Study," *The Cirlot Agency*, 28-Nov-2017. [Online]. Available: https://pr.cirlot.com/faa-and-assure-announce-results-of-air-to-air-collision-study/. [Accessed: 10-Mar-2020].

[21] K. Burke, "How Does a Self-Driving Car See?," *NVIDIA*, 15-April-2019. [Online]. Available: https://blogs.nvidia.com/blog/2019/04/15/how-does-a-self-driving-car-see/. [Accessed 15-April-2020].

[22] S. Jung and H. Kim, "Analysis of Amazon Prime Air UAV Delivery Service," *ResearchGate*, 02-Dec-2017. [Online]. Available: https://www.researchgate.net/publication/317389269_Analysis_of_Amazon_Prime_Air_UAV_Delivery_Service. [Accessed: 09-Mar-2020].

[23] Amazon Technologies Inc, P. K. Mishra, and D. Goyal, "Directed fragmentation for unmanned airborne vehicles," *Google Patents*, 10-Jun-2016. [Online]. Available: https://patents.google.com/patent/US9828097B1/en. [Accessed: 11-Mar-2020].

[24] P. Patel, A. A. Stec, T. R. Hull, M. Naffakh, A. M. Diez-Pascual, G. Ellis, N. Safronava, and R. E. Lyon, "Flammability properties of PEEK and carbon nanotube composites,"

ScienceDirect, 14-Jul-2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0141391012002741. [Accessed: 11-Mar-2020].

[25] “Crumple Zone,” *Crumple Zone - an overview*. [Online]. Available: https://www.sciencedirect.com/topics/engineering/crumple-zone. [Accessed: 11-Mar-2020].

[26] “FAA Releases Aerospace Forecast,” Federal Aviation Administration, 08-May-2019. [Online]. Available: https://www.faa.gov/news/updates/?newsId=93646. [Accessed: 31-Mar-2020].

[27] Ball and Spoke model of a cyclopentadienyl ring. University of California, Los Angeles.

[28] “Climate Change: Atmospheric Carbon Dioxide: NOAA Climate.gov,” *Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov*, 19-Sep-2019. [Online]. Available: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide. [Accessed: 11-Feb-2020].

[29] 60 M. Staff, “Amazon unveils futuristic plan: Delivery by drone,” 03-Dec-2013. [Online].

[30] *Giant delivery drones are coming, but at what cost?* The Verge, 2019.

[31] *High-resolution image on an Amazon Prime Air UAS currently in development by Amazon, Inc.*. Amazon.com, Inc., 2016.

[32] *UPS delivery drone returning to its roof base on a modified UPS delivery truck.* United Parcel Service of America, Inc., 2017.

[33] *High-resolution image on an older Amazon Prime Air UAS currently in development by Amazon, Inc.*. Amazon.com, Inc., 2016.

[34] “Environment,” *SodaStream*. [Online]. Available: https://sodastream.com/pages/environment. [Accessed: 29-Feb-2020].

[35] J. Hoelzen, Y. Liu, B. Bensmann, C. Winnefeld, A. Elham, J. Friedrichs, and R. Hanke-Rauschenbach, “Conceptual Design of Operation Strategies for Hybrid Electric Aircraft,” *Energies*, vol. 11, no. 1, p. 217, January, 2018, doi: 10.3390/en11010217

[36] “Whipped-Cream Charger,” *Wikipedia*. [Online]. Available: https://en.wikipedia.org/wiki/Whipped-cream_charger. [Accessed: 13-April-2020].

[37] “Package Delivery by Drone (Part 135),” *Federal Aviation Administration*, 01-Oct-2019. [Online]. Available: https://www.faa.gov/uas/advanced_operations/package_delivery_drone/. [Accessed: 31-Mar-2020].

[38] “U.S. Energy Information Administration - EIA - Independent Statistics and Analysis,” U.S. Energy Information Administration (EIA) - Source, 14-Apr-2015. [Online]. Available: https://web.archive.org/web/20171028144847/https://www.eia.gov/outlooks/archive/aeo15/electricity_generation.cfm. [Accessed: 31-Mar-2020].

[39] "Onshore Wind Power Now as Affordable as Any Other Source, Solar to Halve by 2020," *IRENA*, 13-January-2018. [Online]. Available: https://www.irena.org/newsroom/pressreleases/2018/Jan/Onshore-Wind-Power-Now-as-Affordable-as-Any-Other-Source. [Accessed: 2-April-2020].

[40] Service, Robert F, "Giant batteries and cheap solar power are shoving fossil fuels off the grid," *American Association for the Advancement of Science*, 11-July-2019. [Online]. Available: https://www.sciencemag.org/news/2019/07/giant-batteries-and-cheap-solar-power-are-shoving-fossil-fuels-grid. [Accessed: 2-April-2020].

[41] "Our Story - About Us: Binghamton University," *About Us - Binghamton University*. [Online]. Available: https://www.binghamton.edu/about/our-story.html. [Accessed: 20-Feb-2020].

[42] *Overhead view of the Binghamton University- State University of New York Campus*. Scholarship-Positions.com, Inc., 2019.

[43] "Binghamton University," *Binghamton University - Binghamton University*. [Online]. Available: https://www.binghamton.edu/. Accessed: 11-Feb-2020.

[44] "Binghamton University," *Data USA*. [Online]. Available: https://datausa.io/profile/university/suny-at-binghamton. [Accessed: 20-Feb-2020].

[45] "Binghamton University, SUNY," *Forbes*. [Online]. Available: https://www.forbes.com/colleges/suny-at-binghamton/#7ac2a5b56ea0. [Accessed: 23-Feb-2020].

[46] "Binghamton University--SUNY Overall Rankings | US News Best Colleges," *U.S. News & World Report*. [Online]. Available: https://www.usnews.com/best-colleges/suny-binghamton-2836/overall-rankings. [Accessed: 11-Feb-2020].