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Enhancing Cargo Transportation by Reducing Airship Operating Costs

** All authors contributed equally to this memo. The names are listed alphabetically by first name.*

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Abstract

The cargo sector, contributing 8% of global greenhouse gas emissions, requires immediate action as the transportation industry gradually shifts towards greener energy solutions. In place of conventional cargo transportation, airships provide both an emission-free and cost-effective alternative. However, the cost of helium is increasing with time, making helium unsustainable to use for current state-of-the-art airships in the long term. This report explores and examines a variety of strategies and methods to make the transition to airships smoother, addressing cost concerns to ensure a beneficial shift for both aviation and cargo sectors. The main methods that have been explored and proposed are the conservation of helium through the usage of superheated steam, recycling helium using a cryogenic distillation system, ensuring the use of an efficient propulsion system, ensuring the use of an efficient electrical system—a hydrogen fuel system, and a path-finding algorithm (A* algorithm) to navigate through hazardous weather. By implementing these systems, sustainable airships can be achievable due to the concern of high-costs being greatly minimized.

Introduction

1.1 Climate Change and Cargo Transportation

Battling carbon emissions has been at the forefront of our efforts to combat climate change. Billions of tons of cargo are transported around the world each year by trucks, planes, ships, and trains. This extensive transportation of cargo accounts for about 8% of global greenhouse gas emissions, or over 4 billion metric tons of greenhouse gasses (CO_2, nitrous oxides, etc.) Each mode of current cargo transportation presents its own environmental challenges. For example, maritime travel has released tens of thousands of tons of oil into the ocean, causing severe damage to the environment. [1] Additionally, sulfur oxide, which is released by ships in their gas exhaust, contributes to acid rain, further harming not only aquatic biomes but also terrestrial biomes. [2] Aviation, while contributing less to greenhouse gas emissions overall, release high amounts of nitrous oxide at very high altitudes, leading to current ozone depletion being exacerbated. [3] - [5] Finally, road transport contributes immensely to carbon dioxide emissions, the most prevalent greenhouse gas in the atmosphere, as well as particulate matter, degrading air quality and creating health risks for humans. All together, these greenhouse gases pose a significant threat to human beings and the planet, emphasizing the need for sustainable alternatives in cargo transport.

1.2 Airships: A sustainable alternative

Considering these issues, airships present a feasible, environmentally friendly alternative to cargo transportation. Airships have long been used, normally for advertising and tourism. However, the practice of airships for transporting cargo is not widely used due to the high operating costs. The operating costs of airships are consistently rising along with the rising costs of helium. Since 2020, helium costs have almost doubled, from a mere $7.57 per cubic meter to a whopping $14 as of 2023. [6] This is attributed to a worldwide helium shortage, as it is the only non-recoverable element, thereby increasing the operating costs of airships.

Despite these challenges, airships produce little to no greenhouse gas emissions, meaning that they have a significantly lower environmental impact compared to conventional air travel. Airships do, however, still release a slight amount of greenhouse gases, mainly carbon dioxide, due to burning fuel for propulsion systems and helium generation (as helium is oftentimes generated through harmful extraction processes). Airships require much less space in comparison to planes as well with regards to takeoff, land, and refuel, requiring much less invasive infrastructure, which helps preserve habitats which would otherwise be destroyed.

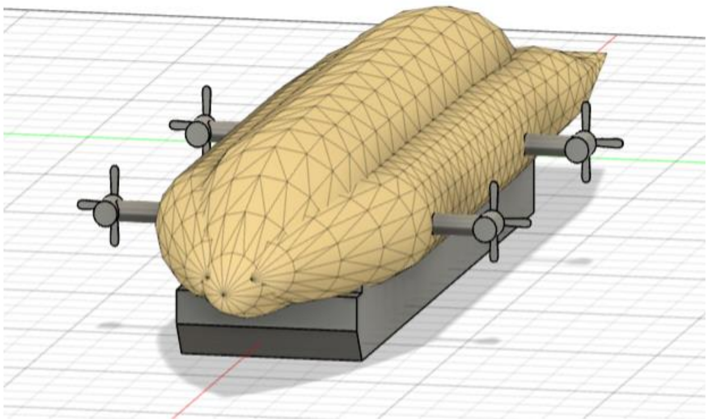


Figure 1: Airship Prototype

In this paper, the team proposes an airship for cargo transportation (see Figure 1: Airship Prototype) which utilizes superheated steam as well as helium recycling through the processes of cryogenic distillation and pressure swing adsorption. Superheated steam would be generated in a boiler reactor. This airship model decreases the operating costs of airships immensely by decreasing the amount of helium, providing a method of transport which can ship tens of thousands of tons of cargo in one trip that outweighs conventional cargo transport such as shipping in both cost and logistics.

Related Works

Cargo airships like the Lockheed Martin Hybrid Airship, Pathfinder 1, and ATLANT Cargo Airship represent significant advancements for airships in logistics and transportation, particularly for remote and hard-to-reach areas. The Lockheed Martin Hybrid Airship, for example, is designed with a unique combination of technologies that enable it to perform in environments where traditional aircraft or ground vehicles might struggle. It utilizes a helium-filled envelope to provide lift, but unlike conventional blimps, it also relies on aerodynamic lift generated by its unique shape. This hybrid approach allows the airship to maintain stability and maneuverability even under varying load conditions. Additionally, the airship is equipped with vectorable engines that give it the capability to take off and land vertically, allowing it to access areas without runways or other infrastructure. [7] This flexibility makes it an ideal solution for transporting goods, humanitarian aid, or industrial equipment to remote locations like oil fields, mining sites, or disaster-stricken areas.

The Pathfinder 1 airship similarly aims to redefine cargo transportation by focusing on the ability to carry large, heavy, and oversized loads. Its design features a rigid structure with a large payload bay, and it is equipped with advanced control systems that enable precise handling even in challenging conditions. The airship’s vertical takeoff and landing capability, combined with its ability to hover, makes it possible to deliver cargo directly to areas without landing facilities. [8] This is particularly useful for operations in dense forests, mountainous regions, or isolated islands where building a landing strip would be impractical or environmentally damaging. However, our airship, using a mix of superheated steam and helium will only need about eight bags of helium compared to the Pathfinder’s thirteen bags. Furthermore, using cryogenic distillation, the team will be able to recycle the helium saving 95% of it. As helium is a scarce element, it is imperative that we conserve it.

The ATLANT Cargo Airship takes a different approach by emphasizing scalability and adaptability. Its modular design allows operators to customize the airship for different types of cargo, whether it be heavy machinery, construction materials, or even large groups of passengers. The airship’s design includes a large cargo hold that can be modified with different configurations depending on the mission requirements. Moreover, the ATLANT airship incorporates advanced materials and construction techniques to ensure durability and efficiency, while also being equipped with state-of-the-art navigation and control systems. [9] This makes it a versatile platform that can be used across various industries, from logistics and construction to tourism and emergency response. By combining these features, the ATLANT airship not only provides a practical solution for transporting cargo but also contributes to reducing the environmental impact of logistics operations by offering a greener alternative to traditional methods.

Helium Leakage

2.1 Issue of Helium Leakage

An airship requires hundreds of thousands of cubic meters of helium for lift, even in the absence of cargo. Given the scarcity of helium, a significant drawback of current airships is the high propensity for helium leakage from the airship's envelope due to the current materials used in its construction. This leakage not only results in substantial operational costs but also poses a challenge to the sustainability of airship operations. Helium, being a finite and non-renewable resource, is expensive and increasingly difficult to procure. Therefore, the development of an affordable yet durable material to prevent helium leakage is crucial. This material must be lightweight to maintain the airship's buoyancy while offering superior resistance to helium permeation and environmental wear and tear. Addressing this issue could lead to more economically viable and environmentally friendly airship designs, making them a more efficient option for cargo and passenger transport in the future.

2.2 Envelope Material

The team considered 5 different materials, Aerogels, Nanoporous Silica, Nanoporous Polyurethane Foams, Mylar, and Tedlar. Aerogels, nanoporous silica, and nanoporous polyurethane are relatively more expensive materials in comparison to mylar and Tedlar. Despite being nanoporous, these materials still allow helium to escape, making them less effective than non-porous materials like Mylar. [10][11]

Mylar, a polyester film brand also known as biaxially-oriented polyethylene terephthalate, is renowned for its low gas permeability, durability, chemical resistance, flexibility, and overall cost-effectiveness.[12] By combining this material with Tedlar, a polyvinyl fluoride film known for its exceptional durability, chemical resistance, and UV stability, the envelope of the airship can significantly reduce helium leakage and withstand harsh weather conditions encountered in Earth's atmosphere, such as UV rays. [13]

The challenge of combining Mylar and Tedlar to create a unified material for airship envelopes can be addressed through the process of adhesive lamination. This technique bonds two or more layers of materials together using an adhesive, and in this case, liquid polyurethane is selected for its strong bonding properties. To laminate Tedlar and Mylar, the first step involves applying a thin, even layer of adhesive to one or both surfaces, which can be achieved using methods such as spraying, rolling, or brushing. Once the adhesive is applied, the second step includes carefully aligning and pressing together Mylar and Tedlar sheets, either manually or with a lamination machine, ensuring that even pressure is applied across the entire surface to avoid the formation of air bubbles. The final step is curing the adhesive, which may require the application of heat or pressure for a specified duration. After the curing process is complete, the newly laminated Mylar-Tedlar material is ready for use in constructing the airship envelope. This method combines the advantageous properties of both materials—Mylar's low gas permeability and durability with Tedlar's chemical resistance and UV stability—resulting in a more effective and resilient solution for reducing helium leakage and withstanding harsh environmental conditions.

2.3 Superheated Steam

As previously mentioned, helium is a scarce and costly resource, which is part of the reason airships have not been used prominently. In place of helium, the team looked into two alternatives: hydrogen and superheated steam, both of which are more affordable in comparison to helium. However, hydrogen is known for its flammability, a factor which has caused known airship disasters in the past.

Superheated steam, however, can be produced at large volumes in boiler reactors; it has no issues with scarcity or flammability. The saturated steam generated in the boiler will be converted to superheated steam using a radiant superheater. The usage of superheated steam increases the viability of this eco-friendly zero-emissions cargo transport method, which will serve to decrease the net emissions of the cargo transportation industry. Along with helium, the airships will use superheated steam generated from boiler reactors, which come out at temperatures of 285 degrees Celsius and provide a superior method of lift compared to helium during takeoff. As airships fly at 3000 meters, the takeoff process of the airship can be conducted by superheated steam comprising ⅓ of the airship's volume, and at sea level, with an initial temperature of 350 degrees Celsius, it has a lift capacity 3.2% higher than that of helium. However, heat loss over time means that the superheated steam will only be superior to helium as a method of fuel before it condenses, which limits its effectiveness to the takeoff phase of the flight and necessitates a method of disposal to maintain equilibrium for the later sections. Below, Figure 2a (altitude vs time) and Figure 2b (temperature vs time) are shown detailing how a flight of an airship with ⅓ of its volume filled with superheated steam would occur:

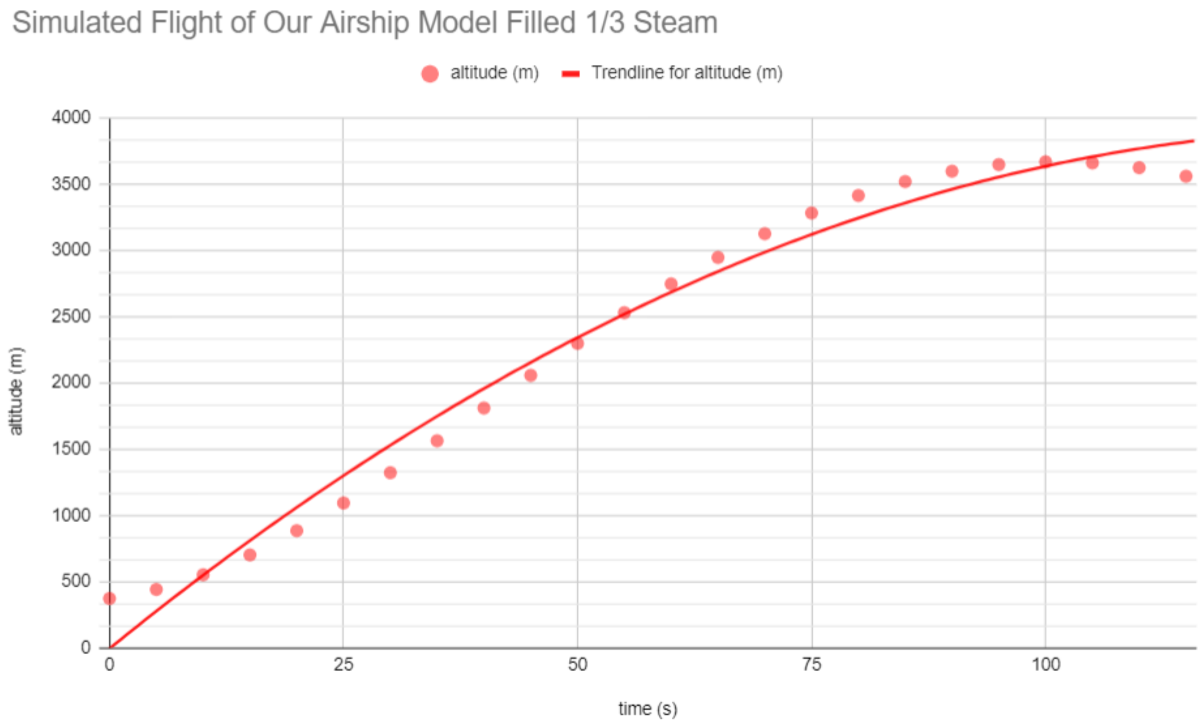


Figure 2a: graph showing the altitude levels in flight of an airship with a volume of 280000m^3 and 27000kg extra cargo lifted by ⅓ of steam initially heated to 285 degrees C and ⅔ helium, shows that steam can carry an airship loaded with cargo to flying elevation of 3000m

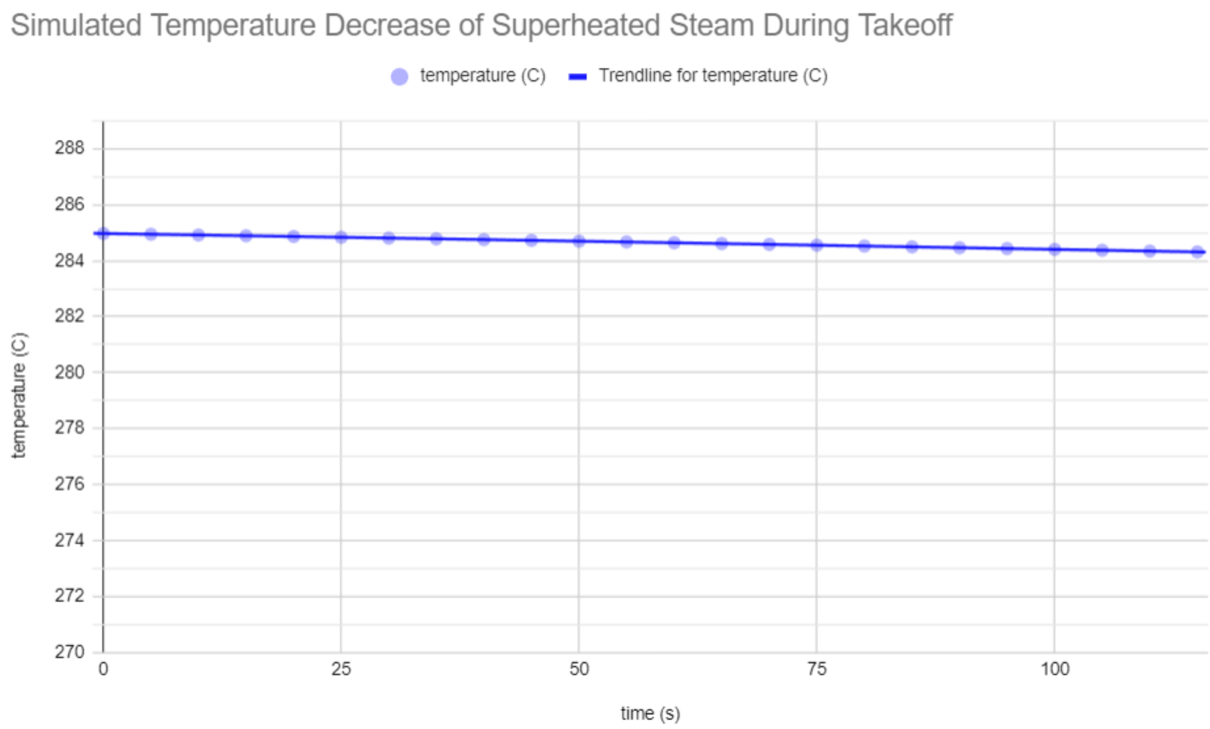


Figure 2b: Models temperature loss of superheated steam over time, shows that the heat loss is minimal and steam will not condense during takeoff phase.

According to Figure 2a, superheated steam can carry up to 0.84 kg/m^3 of total mass to the flying altitude of an airship (3000m). The usage of superheated steam was simulated used Python which can be accessed at: https://github.com/ATal12/SuperheatedSteamSimulation-NASA-Internship-2024. Throughout the duration of the simulation, each cubic meter of superheated steam generated 1.202 Newtons more upward force on average than the same volume of helium would. Assuming that the maximum amount of cargo is loaded, shortly after reaching flying altitude, the airship's altitude will start to decrease due to heat loss to the surroundings if it keeps relying on superheated steam as the primary fuel source. Therefore, as soon as the airship reaches 3000 meters, it will transition from steam usage to using the helium fuel and start releasing the steam through a set channel before it condenses to avoid a sudden increase in airship mass.

The team has not determined the mechanism by which the steam shall be released yet, but there are two options:

1. Filling the steam in separate sections of the airship that can be released when necessary

   This would potentially pose a hazard to civilians below, and is an unsafe method of disposal.

2. Releasing the steam through the valve.

   This could expose the airship to outside air, and the consequences of adding a valve to the airship's hull would need to be further explored before implementation.

Further research of a release mechanism would be required before full implementation of this steam solution. Additionally, the simulation only simulated the airship's takeoff phase; the flying phase is complex, as the airship has to maintain equilibrium by adjusting the pressure inside the hull [14].

In summary, the airship will use steam to generate lift during takeoff, and then transition to using helium when it reaches flying altitude and needs to maintain equilibrium. This airship design would use around 33% less helium per flight, which increases the viability of airships as a cargo transportation method. With further research, the team could conclusively determine the v in iability of this solution over the duration of a full airship flight.

2.4 Monitoring Helium Outputs

While Tedlar and Mylar can greatly reduce costs and potential helium leakages due to their weather-resistant materials, it is still possible for helium to leak out. To thoroughly address this issue, a helium leak detection sensor is proposed. The team looked into three gas sensors: Figaro TGS 822, Ion Science GasCheck G, and Honeywell AWM5000 series. Not only is the Honeywell AWM5000 series extremely cost effective, but it is lightweight, a crucial factor in maximizing the cargo load of our airship. Compared to the other sensors we looked at which were $780 and $560 each, the Honeywell AWM5000 was only $230. [15]

The Honeywell AWM5000 series gas sensor offers high sensitivity, fast response, low power consumption, and accurate measurements, making it ideal for detecting helium leaks in airships. To enhance the effectiveness of the detection system, the sensor will be mounted on a motorized gimbal. This setup will allow the sensor to move and scan different areas of the airship, ensuring complete coverage and detection of any helium leaks. The continuous detection of pressure will always be compared against the normal expected pressure of 0.07 pounds per square inch, providing real-time monitoring and quick identification of any discrepancies. This strategic placement and mobility of the gas sensor ensure that the entire airship is thoroughly checked for potential leaks, thereby maintaining its safety.

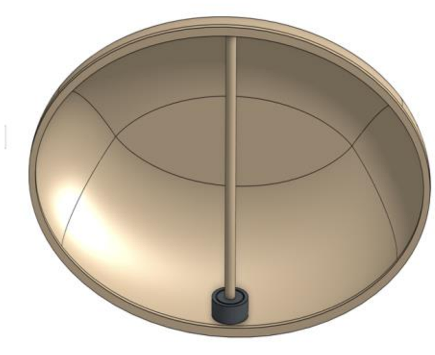


Figure 2c. Diagram of Interior of the Envelope containing the Honeywell AMW5000 Series

2.5 Recycling Helium

Cryogenic distillation is a process used to separate gasses from one another by utilizing the differences in boiling points for different elements. [16] This process can be used to separate helium from other elements very easily, due to the fact helium has the lowest boiling point out of every single element, at -268.92C. The element that has the next lowest boiling point is hydrogen, at -252.89C, so as long as the temperature goes below -252.89C, helium should theoretically be completely isolated from other elements. [17] - [19] This process can be used to recycle helium. Before helium enters the cryogenic distillation unit, it will go through a pressure swing adsorption (PSA) unit, to remove impurities, ensuring that the gas entering the cryogenic distillation unit is purer, thus making the cryogenic distillation process more efficient and effective.

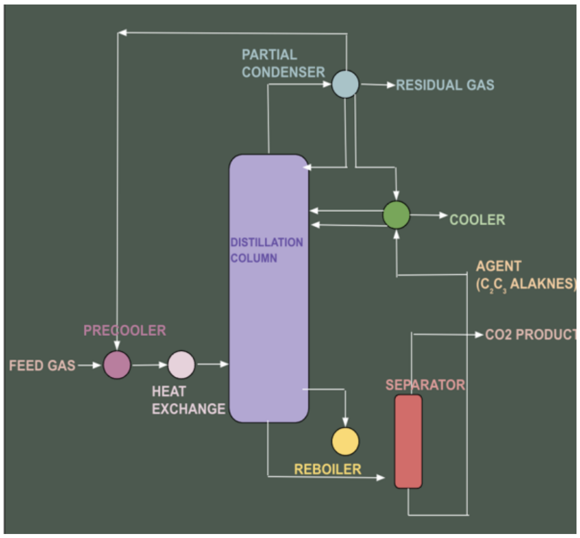


Figure 2d. Diagram of Cryogenic Distillation Unit

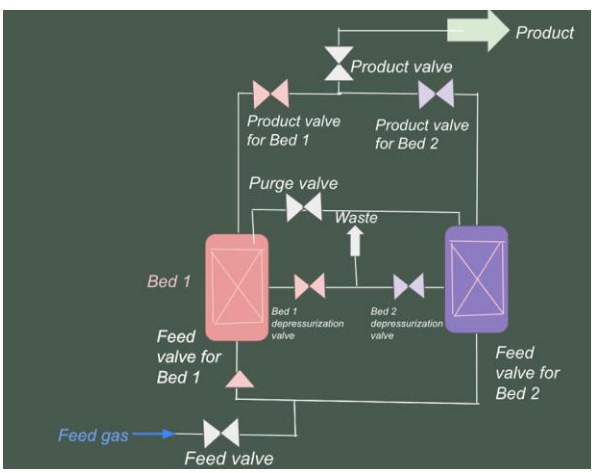


Figure 2e. Diagram of a Pressure Swing Adsorption Unit

The way a pressure swing adsorption unit works is through using adsorbents such as zeolites or activated carbon to absorb gasses such as nitrogen and oxygen at a high pressure.

Additionally, recycling helium further reduces the amount of helium consumed by airships. By implementing cryogenic distillation units, helium can be reused often. This not only reduces the costs associated with using helium, but also conserves helium, which is both scarce, costly, and a major factor as to why the usage of airships has been hesitating.

Cryogenic distillation units separate elements through the utilization of different boiling of each element; each element can be separated through evaporation. There's a distillation column where all these different elements get stored, and the lower the boiling point, the higher the gas is in the column.

The helium run through the cryogenic distillation units would be stored in storage tanks, allowing effective storage of helium. [20]

Overall, if the team is able to use the superheated steam, then the amount and cost of helium needed would lessen by about a third (33%). If the team is saving 33% of helium, the team would only need to use 67% of what would need to be used in a traditional airship. This coupled with the cryogenic distillation unit saving 95%, the team would only need 3.5% of the cost of helium per refill in comparison to a traditional airship of this size. (This is calculated as 67% – the percentage of helium the team's airship prototype requires compared to a traditional one – multiplied by 5% – the percentage of helium needed to refill the airship after saving 95% – resulting in 3.5%.)

Electrical and Propulsion Considerations

With the rising need to reduce and prevent carbon emissions, an eco-friendly power source is one of the main focuses of the new airship design. Given this constraint, the team investigated two possible power sources: nuclear fission and solar power. Nuclear power was deemed impractical due to numerous issues, primarily safety. Additionally, nuclear fission is not 100% environmentally sustainable either, given that it produces radioactive waste, which, when released, causes issues for habitats and organisms [21]. However, solar power doesn't maintain an advantage either. To power the immense airship, roughly 19,000 solar panels would be needed to generate the required electricity. Additionally, solar panels can't produce power all day and require a large battery reserve to supplement them [22]. Therefore, another renewable and practical electrical source is necessary, and thus came the idea of hydrogen fuel cells [24].

3.1 Electrical

The airship's primary electrical system consists of hydrogen fuel cells, a water electrolysis system, and Tesla Powerpack 2 batteries, all working together to provide a continuous, sustainable power supply [24]. The core of this system includes the Ballard FCvelocity®-HD85 fuel cells, chosen for their high efficiency (60%), optimal power output (85 kW per module), competitive cost ($85,000 per module), and manageable weight (256 kg per module) [25]. Other considered options, like the Hydrogenics HyPM-HD 100 and Plug Power ProGen 80, had either higher costs, greater weight, or lower efficiency, making Ballard the superior choice. The airship has 40 fuel cell modules, each providing 85 kW, totaling 3400 kW of continuous power. The fuel cells cost $85,000 each and weigh 256 kg, making the total cost approximately $3,400,000 and the combined weight around 10,240 kg [26].

The process starts with the water electrolysis system, which uses electrical energy to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) [26]. For this scenario, the electrolysis power is supplied by an external generator, so its power requirement is not included in the airship's power budget. The hydrogen gas produced is immediately fed into the fuel cells. Oxygen, a byproduct of electrolysis, is released into the atmosphere or used for other onboard needs. In the fuel cells, hydrogen molecules are split into protons and electrons at the anode. The electrons travel through an external circuit, creating an electric current. The protons move through a membrane to the cathode, combining electrons and oxygen to form water. The overall reaction in the fuel cell is 2H2 + O2 >> 2H2O + electricity [22]. The electricity generated by the fuel cells is used to power the airship's engines and other electrical systems. Tesla Powerpack 2 batteries provide a buffer, storing excess electricity to smooth out demand fluctuations and ensure a stable power supply [26]. These batteries have a total capacity of 2600 kWh, cost approximately $2,040,000, and weigh 20,080 kg [27].

This hydrogen fuel cell system is superior to the previously discussed solar panel system for several reasons. First, hydrogen fuel cells provide a continuous power supply, independent of weather conditions or time of day [22]. Solar panels, while effective during daylight hours, cannot generate power at night or during poor weather, necessitating large battery storage to ensure continuous operation. Additionally, fuel cells have an efficiency of around 60%, while solar panels, even the most efficient ones, typically offer around 22-25% efficiency [28]. The higher efficiency of fuel cells means more effective use of the energy source. Furthermore, solar panels require significant surface area to generate the same amount of power, which could be challenging to implement on an airship with limited space [29]. The hydrogen fuel cell system, including the electrolysis system and batteries, occupies less space and is more manageable in terms of weight distribution.

3.2 Propulsion

The propulsion system of the airship is built around four MagniX magni500 electric engines [30]. Each engine provides a maximum power output of 560 kW, totaling 2240 kW for all four engines. These engines are chosen for their high efficiency, reliability, and suitability for electric aviation applications [33]. The total cost of the engines is $1,200,000, with each engine weighing 120 kg, summing up to 480 kg for all four [22].

The engines are paired with Hartzell five-blade composite propellers, specifically designed for optimal thrust and minimal drag [33]. These propellers are known for their efficiency in converting engine power into thrust, reducing fuel consumption, and increasing the overall performance of the airship. The five-blade configuration offers a larger blade area, which enhances the propeller's ability to generate thrust without significantly increasing drag. The composite material ensures durability and reduces the overall weight of the propeller system. These propellers are designed to operate efficiently at the airship's cruise speeds, providing the necessary thrust with minimal energy loss. The high efficiency of these propellers contributes to the overall energy efficiency of the propulsion system, maximizing the use of the power generated by the engines [33].

The chosen propulsion system, with the MagniX magni500 engines and Hartzell five-blade composite propellers, offers several advantages. The MagniX engines provide a high-power output relative to their weight, making them ideal for the airship's propulsion needs [30]. Electric engines like the MagniX magni500 are known for their reliability and lower maintenance requirements compared to traditional internal combustion engines [30]. The combination of high-efficiency engines and advanced propellers ensures optimal thrust and energy efficiency, allowing the airship to operate effectively over long distances. Moreover, the use of electric engines powered by hydrogen fuel cells ensures a clean and renewable energy source, significantly reducing the environmental impact compared to traditional fossil fuel engines [22].

By leveraging advanced technologies in both the electrical and propulsion systems, the airship achieves a highly efficient, reliable, and sustainable operation, setting a new standard for large-scale airborne transportation. The integration of these systems ensures continuous power supply and optimal thrust, making the airship a superior choice for long-distance and heavy-lift operations.

Accounting for Harsh Weather

4.1 Issue of traveling in hazardous weather

Airships, which have the potential to carry cargo efficiently due to their vast size, face significant challenges during navigation in harsh weather conditions. While the design of the airship can help in light weather conditions, its capacity to continue doing so in stronger winds and thunderstorms is limited. [34] As previously mentioned, the scarcity of helium is a major reason as to why airships are not used often without hesitance. Such unfortunate weather can cause the airship to go through longer paths, leading to an increase of helium consumption. The financial implications increase when routes are blocked or require extensive detours to avoid hazardous weather. Current airship models, including Hybrid Air Vehicles, address these challenges by enhancing design features and incorporating advanced materials to improve speed and maneuverability in adverse weather. [35] These modifications enable airships to navigate through severe conditions with greater efficiency. While the team also proposes weather-resistant material (see Envelope Material for more), leveraging advanced technology presents additional opportunities for enhancing airship operations. Initially it was considered to train an image classification model— which visually identifies storms or winds and eventually, after the model is further trained, learns patterns to distinguish normal weather and hazardous weather and to steer clear of threatening weather. However, after further research it was determined that airships cannot completely avoid bad weather, but rather it would be better if the path could be optimized as it travels from point to point. Thus, an A* algorithm is proposed to perform automatic path planning.

4.2 Initialization and Set-up

To implement the algorithm, the first step would be gathering weather data. To do this, a Doppler weather radar, a critical tool for meteorologists, will provide updated information regarding weather conditions, including the intensity and speed of storms and wind, the most dangerous conditions airships struggle to navigate. [36] The information will be sent to a weather data processing system, resulting in a real-time weather map. After the weather map is processed, the algorithm will function and be able to return the best path among the dynamic obstacles: dangerous weather.

4.3 Path search algorithm

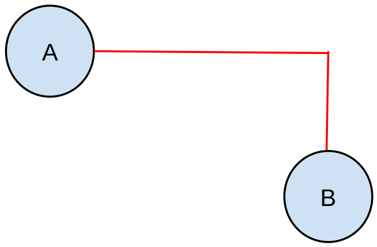
A* algorithm background:

The A* algorithm is a widely used pathfinding and graph traversing algorithm known for its efficiency in finding optimized paths, with a complexity of O(log(n)), meaning it has one of the fastest timing complexities, suitable for real-time scenarios. [37] The A* algorithm is comprised of the strengths of Dijkstra’s algorithm— using a cost function f(n) to determine the best path from the start node to the end node. While deciding on the algorithm that would best suit the scenario of an airship navigating through hazardous weather, it was evident that Dijkstra's algorithm is less efficient. With the use of the heuristic distance, the A* algorithm can easily calculate and consider the nodes that are closest to the goal; however, Dijkstra’s algorithm lacks this heuristic function meaning it does not prioritize the nodes that are closest to the goal. [38] Thus, Dijkstra’s algorithm takes a longer time to get to the best path. Ultimately, in the scenario of an airship navigating through dynamic weather conditions, Dijkstra's algorithm will end up constantly performing an exhaustive search to get to the goal.

The A* algorithm uses the cost f(n) function to obtain the shortest path. The formula: f(n) = g(n) + h(n) is utilized which is comprised of the following [37]:

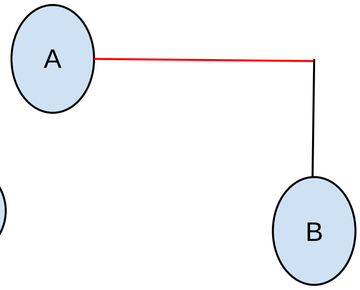
- g(n) = the distance from the start node to the current node
- h(n) = the heuristic distance or precisely the estimate of the current node to the end node.

The best heuristic distance for our use case is the Euclidean distance (see Figure 3c below). While there are a variety of heuristic distances, including Manhattan distance (see Figure 3a), which accounts for limited movements (north, west, east, and south), and Chebyshev distance (see Figure 3b), which is less accurate since it cannot traverse through a variety of angles, Euclidean distance (see Figure 3c) is the best choice because it allows traversal in multiple directions (north, west, east, south, and diagonally at various angles), leading to promising results. [39]



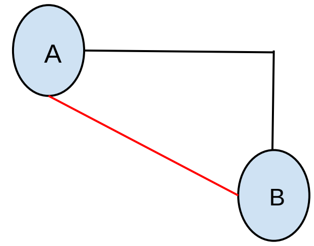
$$D = |x_1 - x_2| + |y_1 - y_2|$$

Figure 3a: Visualization of Manhattan Distance



$$D = max(|x_1 - x_2| + |y_1 - y_2|)$$

Figure 3b: Visualization of Chebyshev Distance



$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

Figure 3c: Visualization of Euclidean Distance

Methodology:

The A*algorithm begins by initializing an open set, containing nodes to be evaluated, and a closed set, containing nodes that have already been evaluated. Starting with the start node in the open list, the algorithm enters a loop where it repeatedly selects the node with the lowest f(n) value from the open list. This node, considered the most promising path towards the goal, is moved to the closed list. If the current node is the goal, the algorithm stops, having found the shortest path. Otherwise, it evaluates each neighboring node. For each neighbor, the algorithm calculates the tentative cost g(n) from the start node through the current node. If this tentative cost is lower than any previously recorded cost, the neighbor's g(n) and f(n) values are updated, and its parent is set to the current node to track the path. The neighbors that are not in the open list are then added to it. Once the goal node is reached, the shortest path is reconstructed by tracing back from the goal node to the start node using the parent pointers. [37]

Interpreting the algorithm in context:

When an airship navigates through bad weather, the A* algorithm helps it find the best route by evaluating various paths based on distance and difficulty. Each segment of the route is assessed for how challenging it is, considering factors like severe weather and static obstacles. The algorithm calculates the most efficient route by balancing the distance to the destination with the difficulty of navigating each segment. As the airship progresses, the algorithm continuously updates the route, using real-time weather and obstacle information to avoid the harshest conditions and ensure the safest, most effective path. This dynamic adjustment helps the airship steer clear of severe weather and obstacles, optimizing its journey for safety and efficiency.

Model:

The algorithm was simulated in this study using Python and is accessible at https://github.com/leyli1215/NASA-astar-algorithm . The simulation considers static obstacles (ie. buildings, towers, skyscrapers) which are represented by purple nodes, as well as moving obstacles (storms and wind) which are represented by red nodes. Figure 3d shows the representation of the path in orange before the moving obstacle at position (1,1) moves upwards and the obstacle at (1,4) moves leftwards.

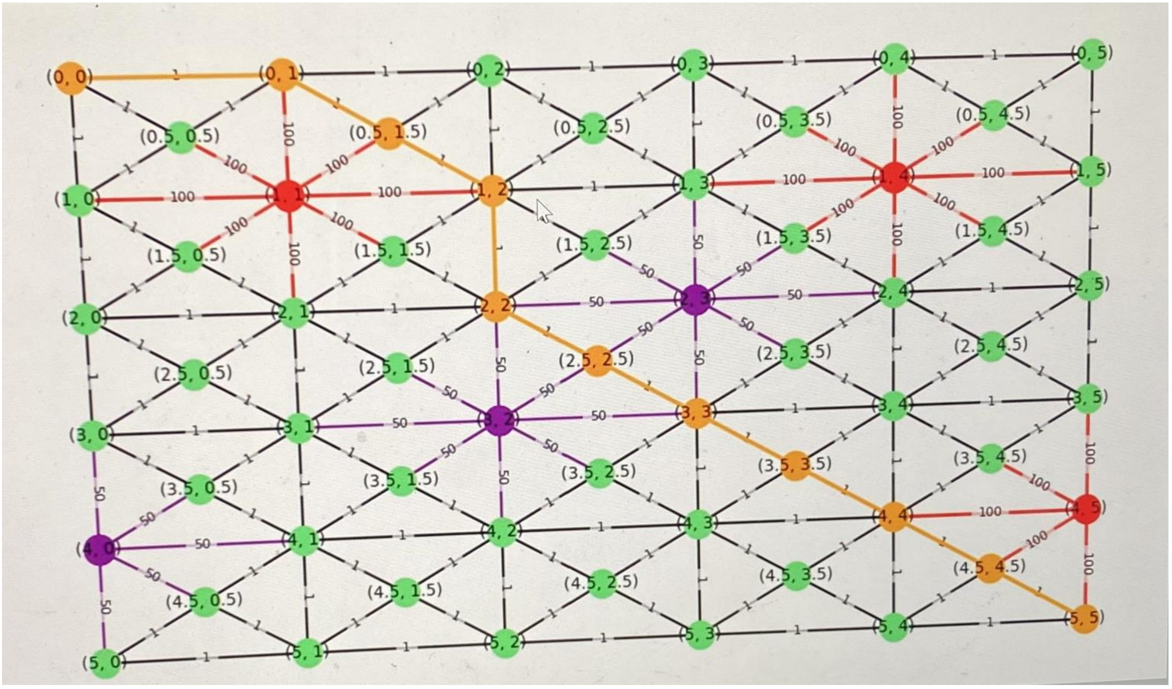


Fig 3d. Visual representation of the current path: [(0,0), (0,1), (0.5,1.5), (1,2), (2,2), (2.5,2.5), (3,3), (3.5,3.5), (4, 4), (4.5, 4.5)(5,5)]

Figure 3e shows the Visual representation of the path after the moving obstacle has moved where the path is recalculated.

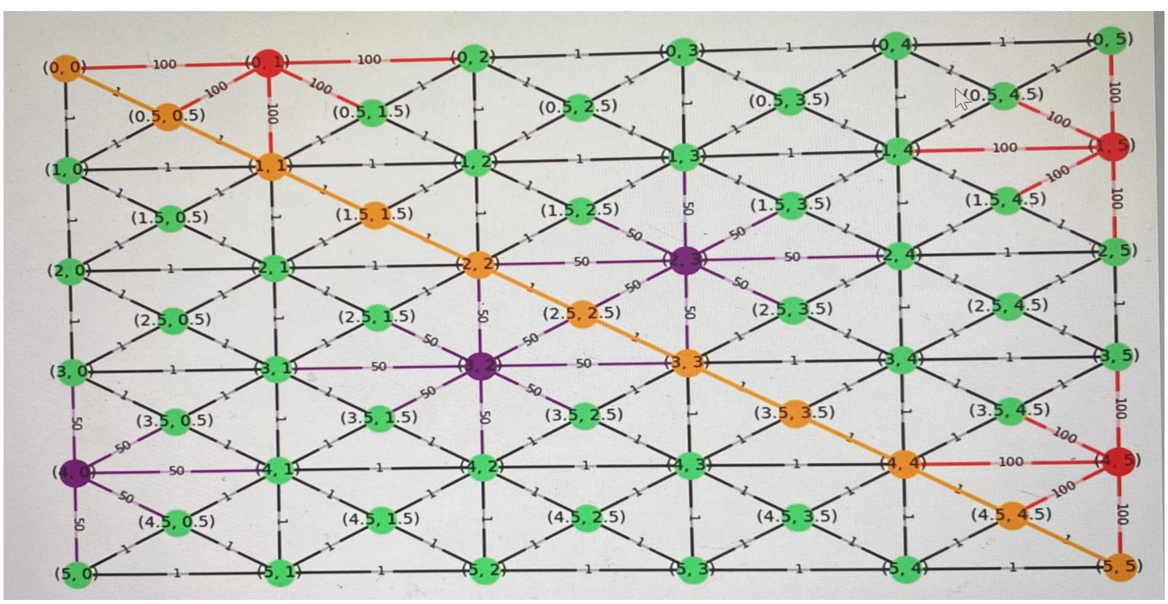


Fig 3e. Visual representation of the new recalculated path: [(0,0), (0.5, 0.5), (1,1), (1.5,1.5), (2,2), (2.5,2.5), (3.5,3.5), (4,4), (4.5, 4.5), (5,5)]

Costs

5.1 Recycling Helium

To calculate the cost of recycling helium, the team first considered the materials involved: Tedlar and Mylar. The team determined the average area of the envelope using the ellipsoid area formula. The team used the average dimensions of the airship, with the semi-major axis (a) being 40 meters (length), and the two semi-minor axes (b and c) both being 10 meters (width and height). In the formula, p represents 1.6075, according to Knud Thomsen's formula.

$$A = 4\pi\left[\frac{(ab)^p + (ac)^p + (bc)^p}{3} \right]^{\frac{1}{p}}$$

By plugging in these numbers, the team calculated the approximate average area of the airship envelope to be 886.2 square meters. The team then determined the cost of Mylar and Tedlar per square meter. Tedlar costs $50 per square meter, and Mylar costs $10 per square meter. By multiplying these costs by 886.2 square meters, the team found the total cost for each material. Tedlar costs $44,310, while Mylar costs $8,662. Combined, the envelope material costs $53,172.

The team then added the costs for the other materials needed for the helium recycling process. The Honeywell gas sensor cost $230. Cryogenic distillation cost $1.6 million. Each helium storage tank cost $50,000. The motorized gimbal was $200. Lastly, the Pressure Swing Adsorption Units cost $300,000. Adding these costs to the Mylar and Tedlar expenses, the total cost comes to $2,053,602.

5.2 Superheated Steam

The specific enthalpy of steam at 285°C can be found from steam tables as 2.952 MMBtu/ton [38], so to produce 1 ton of steam, the team needs 2.952 MMBtu of thermal energy. Considering the efficiency of the nuclear plant (33%), the actual energy needed is higher:

2.952/0.33 =8.945 MMBtu/ton of steam.

With the fuel cost at $0.75 per MMBtu, the cost to produce 1 ton of steam is 8.945*0.75=$6.71

With unit conversions, the cost to produce 1 kg of steam is $0.007; with density of 0.0347, the cost of producing 1 m3 of superheated steam is $0.2. Since our airship needs a total volume of 93,333 m3 of steam, the cost of superheated steam for each flight will be $18,666.

5.3 Electrical & Propulsion

The cost of implementing the overall electrical system for the cargo airship is a significant investment, amounting to approximately $22.9 million. This includes the hydrogen fuel cells, which constitute a major portion of the cost at $2 million, reflecting their cutting-edge technology and high efficiency. The battery system, specifically Tesla Powerpack 2, represents the most substantial expense, totaling $19.2 million due to the need for multiple units to ensure 24-hour operational capability. The industrial-scale electrolysis system, critical for generating hydrogen fuel, adds another $1 million to the costs, highlighting the need for efficient hydrogen production. Additional systems, including avionics and communications, account for $500,000, while the water tanks and recycling systems contribute $200,000 to the total cost. Despite the high initial investment, these costs are balanced by the long-term operational savings and environmental benefits offered by this sustainable energy solution.

Conclusions & Future Works

The cargo sector is responsible for 8% of total greenhouse emissions, and, with the transportation industry moving towards green energy, airships are on the path to becoming a greener and more sustainable alternative to traditional cargo transportation methods. [40] This report has outlined the different methods needed to address the challenges prevalent in transitioning cargo transport to a more aerostatic medium. Additionally, the team has considered the logistical notions by focusing on minimizing cost and weight to ensure the conversion will be advantageous to both the aviation and cargo industries. As helium is a scarce and expensive resource, this proposal will decrease the amount of helium needed by utilizing superheated steam for ⅓ of the flight as well as using helium recycling, making the use of airships more feasible and decreasing the overall resource costs of each flight.

The utilization of cryogenic distillation and pressure swing adsorption when dealing with airships minimizes the amount of helium needed in an airship in the long run, thereby decreasing the operating costs associated with airships tremendously. By decreasing these costs, the appeal and incentives for using airships increases. Currently, cryogenic distillation and pressure swing adsorption units only have the potential to conserve about 95% of helium. However, as time goes on, more developments will be made in cryogenic distillation and pressure swing adsorption, so the team can expect to see the conservation rate of cryogenic distillation and pressure swing adsorption rise.

To address the critical need to reduce carbon emissions, our airship design prioritizes environmentally friendly power sources, leveraging hydrogen fuel cells, water electrolysis, and battery storage to ensure a continuous power supply. Combined with the electric engines and advanced propellers used for propulsion, the airship design sets a new standard for large-scale airborne transportation and achieves significant reductions in environmental impact. Our approach not only provides an eco-friendly method of cargo transportation, but also paves the way for future advancements in sustainable aviation.

The A* algorithm, with its capability to consistently determine the optimal path, can be further augmented by advancements in technology and artificial intelligence. As weather patterns become increasingly dynamic, machine learning techniques can be employed to enhance navigational strategies. By training predictive models to understand and forecast weather movements, it is possible to not only navigate around known obstacles but also anticipate and avoid potential hazards. This future approach leverages machine learning to provide a more proactive and adaptive navigation system, improving the ability to handle both current and anticipated environmental challenges.

While the total expenses including the additions of the systems needed for recycling helium may seem like a large up-front cost, the current average airship on the market of a similar size and cargo capacity would be $40,000,000. On the contrary, our airship would be a total of approximately $26,465,449. In summary, our airship is much more cost-effective compared to an average cargo airship because the difference would be approximately 13,534,551.

References

[1] Y. Wang, S. Yang, and Y. Liu, "Industrialised fishing nations largely contribute to floating plastic pollution in the North Pacific subtropical gyre,," Sci. Rep., vol. 12, no. 1, p. 12208, Jul. 2022. [Online]. Available: https://www.nature.com/articles/s41598-022-16529-0. Accessed Jun. 29, 2024.

[2] International Maritime Organization, "Sulphur 2020 – cutting sulphur oxide emissions," Accessed Jun. 30, 2024. [Online]. Available: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx#:~:text=Some%20ships%20limit%20the%20air,engine%20and%20boiler%20exhaust%20gases

[3] S. Drysdale et al., "Electrification of offshore installations via offshore wind integration," Nat. Commun., vol. 12, no. 1, p. 672, 2021. Accessed Jun. 30, 2024. [Online]. Available: https://www.nature.com/articles/s41467-020-20771-3

[4] A. Skowron, D. S. Lee, R. R. De León, L. L. Lim, and B. Owen, "Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts," Nature Communications, vol. 12, no. 1, Jan. 2021. doi: https://doi.org/10.1038/s41467-020-20771-3. Accessed Jul. 17, 2024.

[5] "New shipping fuel standards to reduce sulphur oxides in the Mediterranean by 80%," Mobility and Transport, Dec. 16, 2022. Available: https://transport.ec.europa.eu/news-events/news/new-shipping-fuel-standards-reduce-sulphur-oxides-mediterranean-80-2022-12-16_en#:~:text=Sulphur%20oxides%20are%20exhaust%20gases. Accessed Jul. 18, 2024.

[6] "The era of cheap helium is over—and that's already causing problems," MIT Technology Review. Available: https://www.technologyreview.com/2024/02/25/1088930/global-helium-market-semiconductors/#:~:text=The%20global%20helium%20market%20has. Accessed Jul. 24, 2024.

[7] "U-2S RECONNAISSANCE AIRCRAFT THE NEWEST GENERATION OF AN AMERICAN ICON HYBRID AIRSHIPS THE ROAD NOT NEEDED." Available: https://www.lockheedmartin.com/content/dam/lockheed-martin/aero/documents/hybridAirship/HybridAirshipLitho.pdf. (accessed Jul. 24, 2024)

[8] "Explore Pathfinder 1 Airship - Lighter Than Air (LTA) Research," *Lighter Than Air*, 2022. https://www.ltaresearch.com/technology (accessed Jul. 24, 2024).

[9] "ATLANT Cargo Airship," *Atlas LTA Advanced Technology*. https://atlas-lta.com/atlant_cargo_airship/ (accessed Jul. 24, 2024)

[10] "What Is Mylar® Film Used For | Uses for Mylar® Film | Tekra Fundamentals," *www.tekra.com*. https://www.tekra.com/resources/tekra-fundamentals/what-mylar-film-is-used-for (accessed Jul. 19, 2024)

[11] Poliuretano.it, “Thermal conductivity rigid polyurethane foam,” *Poliuretano.it*. [Online]. Available: https://www.poliuretano.it/EN/thermal_conductivity_polyurethane.html. [Accessed: Jul. 24, 2024].

[12] “DuPont™ Tedlar® PVF film - American Durafilm,” *American Durafilm*, Oct. 25, 2023. https://americandurafilm.com/film-distribution/tedlar-film/ (accessed Jul. 19, 2024).

[13] LearnChemE, “Steam Tables (.xlsx, .csv, .json),” LearnChemE. [Online]. Available: https://learncheme.com/student-resources/steam-tables/. [Accessed: Jul. 24, 2024].

[14] [2] Softschools, “Specific Heat Formula,” Softschools. [Online]. Available: https://www.softschools.com/formulas/physics/specific_heat_formula/61/. [Accessed: Jul. 24, 2024].

[15] Honeywell, AWM5000 Series Microbridge Mass Airflow Sensor. [Online]. Available: https://prod-edam.honeywell.com/content/dam/honeywell-edam/sps/siot/en-us/products/sensors/airflow-sensors/amplified/awm5000/documents/sps-siot-airflow-awm50000-series-catalog-pages-ciid-50053.pdf. [Accessed: Jul. 24, 2024].

[16] “Cryogenic Helium Purifier ULTRAL He | Air Liquide Advanced Technologies,” Airliquide.com, 2024. Available: https://advancedtech.airliquide.com/markets-solutions/industry/cryogenic-helium-purifier-ultral-he. Accessed Jul. 13, 2024.

[17] "Helium." Breaking Atom. Available: https://www.breakingatom.com/elements/helium. Accessed Aug. 15, 2024.

[18] “Helium Recovery Systems,” Laco Technologies, Available: https://lts.lacotech.com/c/production-leak-test-systems/helium-leak-test-solutions/helium-gas-management/helium-recovery-systems. Accessed Jul. 14, 2024.

[19] “What is a Helium Recovery System?” Cincinnati Test Systems, Available: https://www.cincinnati-test.com/blog/what-is-a-helium-recovery-system. Accessed Jul. 14, 2024.

[20] National Energy Technology Laboratory, "Commercial Oxygen: Cryogenic Distillation," *U.S. Department of Energy*. [Online]. Available: https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/commercial-oxygen#:~:text=Cryogenic%20distillation%20separates%20oxygen%20from,removed%20in%20molecular%20sieve%20adsorbers. [Accessed: Jul. 29, 2024].

[21] E. M. Blake and P. M. Cassidy, "Environmental Impact of Nuclear Power: Waste and Safety Concerns," Journal of Environmental Studies, vol. 34, no. 3, pp. 211-224, 2020.

[22] R. K. Mann, "Feasibility of Solar Energy in Large-Scale Aviation," Renewable Energy Journal, vol. 45, no. 6, pp. 333-342, 2022.

[23] Department of Energy, "How Hydrogen Fuel Cells Work," Energy.gov, 2024. [Online]. Available: https://www.energy.gov/eere/fuelcells/how-hydrogen-fuel-cells-work. Accessed 10-Aug-2024.

[24] Ballard Power Systems, "Ballard FCvelocity®-HD85 Fuel Cell Product Sheet," Ballard.com, 2023. [Online]. Available: https://www.ballard.com/products/fuel-cell-products/fcvelocity-hd. Accessed 10-Aug-2024.

[25] Parker Hannifin, "Proton Exchange Membrane (PEM) Electrolyzer," Parker.com, 2024. [Online]. Available: https://www.parker.com/pem-electrolyzer. Accessed 10-Aug-2024.

[26] National Renewable Energy Laboratory (NREL), "Electrolysis of Water," NREL.gov, 2024. [Online]. Available: https://www.nrel.gov/hydrogen/electrolysis.html. Accessed 10-Aug-2024.

[27] Tesla, Inc., "Powerpack 2 Commercial Energy Storage," Tesla.com, 2024. [Online]. Available: https://www.tesla.com/powerpack. Accessed 10-Aug-2024.

[28] MagniX, "Magni500 Electric Propulsion System," MagniX.com, 2024. [Online]. Available: https://www.magnix.aero/magni500. Accessed 10-Aug-2024.

[29] A. T. Anderson, "High Efficiency Electric Engines for Aviation," Aerospace Propulsion Journal, vol. 66, no. 3, pp. 120-132, 2022.

[30] M. R. Greene, "Advanced Propeller Design for Energy Efficiency," Journal of Aeronautical Engineering, vol. 61, no. 6, pp. 497-506, 2023.

[31] General Electric, "Advancements in Electric Propulsion Systems," GE.com, 2024. [Online]. Available: https://www.ge.com/aviation/propulsion-systems. Accessed 10-Aug-2024.

[32] S. A. Doré, "Electrolysis for Hydrogen Production: Technologies and Applications," Energy Science Journal, vol. 39, no. 4, pp. 288-301, 2021.

[33] P. K. Jansen, "Comparative Efficiency of Energy Sources for Aviation," Journal of Aviation and Aerospace Perspectives, vol. 33, no. 7, pp. 455-468, 2024.

[34] “Airships: What They Are, How They Work | Built In,” Built In, 2024. https://builtin.com/articles/airships#:~:text=Airships%20are%20 susceptible%20to%20 bad. Accessed Aug. 07, 2024.

[35] “HAV,” Hybridairvehicles.com, 2024. Available: https://www.hybridairvehicles.com/news/overview/blog/what-impact-will-weather-have-on-airlander-s-operations/. Accessed Aug. 02, 2024.

[36] Earth Observing Laboratory, “How Do Radars Work? | Earth Observing Laboratory,” *Ucar.edu*, 2019. https://www.eol.ucar.edu/content/how-do-radars-work. Accessed Aug .02, 2024

[37] Wikipedia Contributors, “A* search algorithm,” *Wikipedia*, Mar. 10, 2019. https://en.wikipedia.org/wiki/A. Accessed Jul. 28, 2024.

[38] M. Simic, “Dijkstra vs. A* – Pathfinding | Baeldung on Computer Science,” www.baeldung.com, Oct. 24, 2021. https://www.baeldung.com/cs/dijkstra-vs-a-pathfinding

[39] A. Patel, “Heuristics,” *theory.stanford.edu*, Mar. 22, 2024. https://theory.stanford.edu/~amitp/GameProgramming/Heuristics.html. Accessed Aug. 02, 2024.

[40] “How solar-powered airships could make air travel climate-friendly,” FAU Erlangen-Nürnberg, Apr. 24, 2023. Available: https://www.fau.eu/2023/04/24/news/research/how-solar-powered-airships-could-make-air-travel-climate-friendly/. Accessed Aug. 07, 2024.