Team T.U.R.T.L.E.S.
Twin Underwater Rotational Turbine
Linear Energy System

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Dr. Wood,

Please review the attached design proposal for our senior design project. Our project is a dual-propeller ocean driven energy system designed to harness the energy from underwater currents. This report portrays our final design overview, as well as our preliminary designs and various testing procedures. Thank you for your time. Please contact Nicholas Rasoletti at nrasoletti2009@my.fit.edu if you have any further inquiries.

Team TURTLES
Executive Summary

The purpose of the TURTLES dual-spiral turbine design is to successfully harness energy from ocean currents. As currents flow over the turbine body, the force of the currents turns the propeller of the turbine, creating energy. Because of how the turbine will work, the shape of the body is immeasurably important, and thus determining the most efficient body design is paramount. Throughout the senior design process, the main focus was determining the most streamlined body.

Four original body designs were considered for the dual-spiral turbine; Arrowhead, Teardrop, Shield, and Concorde. These designs were required to meet specific criteria to be considered for a prototype. Some of these criterion include safe environmental interaction, having a streamlined body, maintaining effective buoyancy and stability, and requiring as little maintenance as possible. To test the effectiveness of each of the designs, several tests were implemented. A test in a wave tank was performed to test for drag and stability, while a test in the wind tunnel was performed to establish the streamlines over the bodies. The Computational Fluid Dynamics, or CFD, program Fluent was also used to show the streamlines generated by the various bodies. After narrowing down the first four models, it was determined that four new models should be created and tested. These four new model designs are a much better set as they are essentially four types of modifications to the original four models.
Florida Institute of Technology
DMES

Team

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Purpose Statement

The ocean is perhaps the greatest source of energy on the planet. The motion of the ocean creates an incredible amount of kinetic energy, and extracting this energy is paramount for the future. Ocean currents are a major part of this energy generation, but extracting this energy is a major challenge. However, technology is making major progress on this particular issue, and this progress continued with the creation of the dual spiral turbine energy system. This revolutionary design harnesses the energy of ocean currents, allowing for that energy to be distributed and utilized by civilization.
Introduction/Motivations

Looking to the future, it is obvious that the only way to meet global energy demands is to go outside of fossil fuels. Fossil fuel supplies are rapidly declining, and the global energy demands will only increase over time. This means that renewable resources will soon take center stage. Renewable energy is a highly beneficial option for the future, not only because they are eternal, but also because they are much cleaner. Traditional fossil fuels produce CFCs and other harmful gasses, which are highly detrimental to the earth’s atmosphere. Renewable energy has no harmful atmospheric by-products. Now, the oil industry has been controlling the energy industry for a long time, and will not just move aside for newer, cleaner energy options. Therefore, the only real way to move forward with renewable energy is to create energy-harnessing devices that can be so effective that they completely remove the need for fossil fuels. Renewable energy technology is not at that stage yet, but with time comes progress, and the goal of the dual-spiral turbine energy system is to continue to expedite this progress.

Previous testing determined that the Archimedes Screw was an efficient propeller for the design. The next step is to determine the most efficient body shape. Four original designs were considered for the body shape; Arrowhead, Teardrop, Shield, and Concorde. All four are viable options, so the only way to determine which should be used for the prototype is to see how well the various designs meet certain criteria. Some of these criterion include safe environmental interaction, having a streamlined body, maintaining effective buoyancy and stability, and requiring as little maintenance as possible. All of these criterion are extremely important, and the only way to see which designs best meet the criterion is to test each one. To do this, models of each were constructed and put through a series of tests. These tests include drag and stability tests in the wave tank, as well as a test in the wind tunnel to establish the streamlines over the
bodies. The CFD program Fluent must also be used to show the streamlines generated by the various bodies. Once the first round of testing is complete, the two best models from the first test will be altered in an attempt to improve the results, as they will undergo the same testing as the original models. Once this final testing is complete, it should be clear which model will make the best body for future construction of the turbine.
Background

History of Ocean Energy

Although the main demand for renewable energy today is a need for a clean and long-lasting form of energy, it has been seen that the Greeks used the movement of water to turn mills and grind grains. Ever since electricity became a large part of the human race, countless ways of generating energy have been tested and many have failed. A push for a clean and renewable energy source in recent years has become even more evident. Although there are many different forms of renewable energy, one major draw back to energy systems is the availability of the energy sources. Solar power can be slowed by cloud cover, wind power can be stinted by a calm day, yet ocean energy has the distinct advantage of being readily available as planet earth is covered by approximately 72% of water along with constant thermohaline circulation throughout the world’s oceans [1]. Going as far back as the first humans to live on the planet, water has always been a drawing factor to keep a society afloat. Ancient Mesopotamia found its roots along the Tigris and Euphrates rivers, and it is common survival knowledge that if one is lost, walking along a river will sooner than later lead to a town or village. People have always flocked to water sources for its powerful answer to many needs. This new idea of using water for what has emerged as yet another human need to generate energy is a new view and has countless paths that could prove to be successful. Within ocean energy there are several ways energy can be harnessed. Wave movement, tides, and ocean currents all can be used to produce energy. The two main ways ocean energy has been harness thus far is through surface wave movement and tidal power. The use of ocean currents is a fairly new technology with a lot of promise.

While ocean currents rarely reach two meters per second, they contain a good deal of energy due to the density of the seawater [2]. The density of this moving water can be used to
spin a turbine blade, similar to a wind turbine, which is properly aligned with the current. These turbines would be attached to a generator by a shaft, which would then convert rotational motion into energy. Methods of how to transfer this energy to the shore are still being discussed and will be outlined in this report. The use of current systems comes with many considerations and questions that need to be answered to make it possible to generate energy in an efficient manner worth the cost of energy devices. However, studies show that if Florida could harness just 0.1% of the power contained in the Gulf Stream current, the state could power 35% of its electrical requirements [2].

**Existing Technology**

Ocean energy is a form of renewable energy that utilizes the movements of the ocean to derive electrical power as clean and efficiently as possible. Renewable ocean energy, specifically the use of ocean circulation and currents to produce energy has never been at a more exciting point in history than it is now. New technologies and ideas that make concepts once thought preposterous now achievable are helping the ocean energy market to gain ground in the race for a low cost, high production green energy system. In fact, many systems similar to the T.U.R.T.L.E.S. system are already out there and in testing stages. As of right now there is one full sized, fully functioning turbine that harnesses ocean tidal current energy to produce usable energy. This prototype, along with many other less successful prototypes has been produced to convert electrical power from ocean movements.

Tidal energy is one of the oldest forms of energy generation, dating all the way back to 787 A.D. The tide mill was an entrapment used to collect water when the tide was high, and as the tide went back down the water inside the enclosure would drain out and spin a series of paddlewheels. The spinning paddle wheels were connected to other machinery such as mill grains [3].
This design is still implemented today; some farm owners still build tide mills and use them to generate mechanical power to help operate machinery.

Sea Flo is a full-size working prototype that uses Tidal Current Energy to produce electrical power. By design, this prototype was to be mounted on a piling where it is possible to raise and lower it along the piling, thus making it easy to repair and/or maintain. It was constructed in 2003 and worked successfully for three years in harsh marine conditions. [5]
The system produced on Average 300kW and was installed off Lynmouth in Devon. The velocity of the tidal current is on average of about 2 meters per second. This system performed better than predicted. [5]

The successful deployment and use of the Sea Flo project curbed the enthusiasm of other companies interested in the research of possible renewable ocean energy systems. A new system known as SeaGen, created by the same company as Sea Flo, Marine Current Turbine Ltd., is another fully functioning tidal current turbine, which is located off the coast of Strandford Lough. This system uses dual turbines mounted to pilings that look very similar to a wind turbine used for wind energy. It is speculated that the SeaGen system will be used in a “farm” fashion in the future where each particular system is capable of producing 1.2 MW of clean energy [5]. This farm system will be the first commercial use of underwater turbine technology to generate energy.
Florida Atlantic University’s Center for Ocean Energy recently received a large grant and was designated a National Center by the United States Department of Energy [8]. Their system is similar to the T.U.R.T.L.E.S. system in that it is based on a horizontal axis.

At this point the university has smaller prototypes they plan on deploying in the Gulf Stream by mooring the system to the ocean floor and will conduct testing. The projected amount of energy that could be produced by the system in Figure 1 is 20 kilowatts [8]. However, this number has not been tested and proven.
As can be expected, small amounts of data can be found on any of the prototypes listed above, as concepts and ideas in such a new topic can be vital to the success of an energy system. The T.U.R.T.L.E.S. system is considered a dual horizontal axis turbine system, whereas many of the ocean current systems are vertical axis systems. Both types of turbine systems are still largely unexplored and similar in promise.

Those systems that are not utilizing ocean current energy mainly focus on using either surface wave movement or tidal currents. Although both tidal and ocean currents are just that, currents, the process of yielding energy from the two contains significant differences. The main focus of the design of an energy system is the ability to withstand a corrosive marine environment while keeping a low maintenance profile that can efficiently produce renewable energy.

The key reasons as to why tidal energy is such a widely implemented idea is due to the fact that tides are extremely consistent and easily predictable. There are tidal charts and endless amounts of research on tides for almost everywhere in the world, making it easy to design and install a tidal energy system to maximum efficiency [3]. The total potential energy of tidal energy estimated for the entire world is about forty six thousand electrical megawatts (64,000 MWe), which is equal to over four-hundred million megawatt hours per year (400,000,000 MWh/yr) [3].

There is a more technical and updated version of the tide mill currently being put to use in Suffolk England. This design uses a propeller instead of a paddlewheel and a top cover or barrage to entrap a specific head of water. As the tide rises water wants to pour into the entrapment, and as the tide goes down water wants to leave the entrapment. Therefore, no matter which way the tide is shifting, the propeller is always spinning and generating energy [9].
Water current energy is another popular form of ocean energy; however, it is presently at an early stage of development. Major ocean currents are constantly moving and they can reach speeds up to two meters per second, which is roughly four and a half miles per hour. Even though these speeds do not sound too impressive compared to wind speed, water is about eight-hundred times denser than air; thus, an ocean current moving five miles per hour is equivalent to a wind speed of about fifty miles per hour. Also, unlike wind, ocean currents are consistently the same speed; thus, energy generation is constant and easily predictable [2].
The most popular design for current turbines is basically putting a wind turbine underwater in an ocean current.

![Figure 6. Example of underwater turbines][2]

These turbines have rotor blades and a generator, very similar to that of a wind turbine, along with posts to anchor them and keep them stationary. Research has showed that these underwater turbines are just as effective as their wind-turbine counterparts on land. [10] This is extremely important, as there will always be current in the water, but there may not always be wind currents on land.

A popular ocean current turbine, which is implemented today, is the Kaplan turbine. It is a propeller-type water turbine invented by the Austrian professor Viktor Kaplan in 1913. The main reason why the design is such a success is due to the fact that the propellers are able to automatically adjust themselves in order to guarantee maximum efficiency based on the flow properties [11].
History of Archimedes Spiral

Archimedes was a Greek inventor accredited with creating the first propeller, deemed the Archimedes Screw. It was invented primarily for raising water from low to higher land for irrigation purposes. It was an inclined plane spiraled around a central shaft which, when spun, moved the water up the incline and out the top. In the 1700’s, developers started to realize its potential as a propeller system, and started installing it on boats. However, these vessels were still human powered, so this new propeller made almost no improvement on the old paddle propeller. This propeller was eventually used on a hand crank powered submarine called the Turtle, with some success. It wasn’t until the invention of the steam engine that this propulsion system took hold, but that was only the beginning. People started to study and improve the screw to better its performance, but it wasn’t until 1827 that it was patented by Josef Ressel. This didn’t stop people from taking on the daunting engineering task of improving it still. The US was the first country to construct a warship with screw propulsion, and the Royal Navy quickly followed afterward, utilizing a slightly different screw design. It took quite a while, but once the maritime world realized that the screw propeller could be used as a primary means of vessel propulsion, the challenge was no longer to prove its worth, but to improve its efficiency. Further research soon showed that the propeller was not the most efficient design at the speeds necessary. This
was the first step toward the bladed propellers that exist today. Nevertheless, propellers in general all derived from the work of Archimedes and shear mechanical power. [5] [13]

For purposes of the system, a few different styles of propellers were tested in previous years, and it was determined that the screw propeller was very efficient. Most other propeller systems work best in fast flow situations, but the top speed in the Gulf Stream is less than 2 m/s at the surface, with the system being well underwater, meaning that the current speed that the propellers will be experiencing will be relatively low. The Archimedes screw design works well in these light flow conditions. Along with being able to provide the most torque to the generator, the screw prop also lends itself to being weed and debris free because it doesn’t allow anything to snag on it. This was one of the top criteria that was considered when choosing a propeller because if weeds and debris such as rope and even wildlife were to get stuck in the propeller it could render the device useless, not to mention hurt the wildlife. Bladed propellers tend to be more violent to wildlife and are also more susceptible to getting tangled in debris. The surface area of the propeller exposed to the flow is also critical in harnessing power from the current, and although the Archimedes screw does not greatly increase the surface area factor, it doesn’t sacrifice any surface area, so this, along with all the other categories that it excelled in makes it a viable option for the future. Further research will prove if it will end up being the propeller on the turbine prototype when it is constructed.

Environmental Benefits

The use of renewable ocean energy benefits the environment in several different ways. The benefits associated with renewable energy stem from reducing the amount of harmful pollutants that are released into the environment. The primary energy generation processes used today are major contributors to the harmful pollutants mentioned above. By using green energy
in place of the current processes, these negative impacts can be avoided, and a higher quality of the environment can be maintained. This benefit alone is powerful enough to justify taking the time to explore renewable energy. Fossil fuels are also limited in quantity, and the search for more fuel by drilling into the earth can lead to accidents, such as the Gulf of Mexico oil spill. In order to have a true understanding of just how beneficial renewable sources of energy are to the earth and its inhabitants, one must have a good understanding of just how destructive many of the current energy generation processes are to the environment. All aspects of the environment are affected either directly or indirectly by the air pollution created by the burning of fossil fuels. This air pollution seeps into the world’s water systems and is spread to the flora and fauna everywhere [14]. One-third of the nitrogen oxides, two-thirds of the sulfur dioxides, and one-third of the carbon dioxides that can be found in the air are directly due to the burning of fossil fuels [15]. These oxides contribute to the destruction of the ozone layer, as well as to the production of smog.

There are three main types of fossil fuels; coal, oil and natural gas. Going in depth to the processes needed to make coal useful to humans, it can be seen that every step is harmful to the environment. Coal must first be mined, which can sometimes destroy entire mountains in the process. The transportation of the coal causes dust to be released into the air, thus reducing the quality of life around a plant. A typical coal power plant burns about 1.4 million tons of coal a day, which is enough to power a city of about 140,000 people [14]. As touched on earlier, drilling for oil and/or natural gas can be extremely harmful to the surrounding environments. Oil spills affect whole ecosystems for extended periods of time, killing the fish and plants in the area of the spill, as well as leaving close by coastlines uninhabitable. Although the true effects of the impacts fossil fuels have on the world have never been truly “quantified,” causalities are real and
the impacts can only been seen to be growing. Eventually these limited fossil fuels will run out and will need to be replaced with new forms of energy. Along with all of the detrimental impacts to the environment, the current processes discussed above are also inefficient. Much of the energy generated by burning fossil fuels is released into the atmosphere in the form of heat.

All in all, the impacts described above can and will become exponentially worse as the pollution will begin to build up and eat away at the earth’s environment. The implementation of renewable energy systems is a direct answer to all the negative impacts of the current processes. The clean, pollution free, and never ending supply of energy is exactly what the world needs. The use of renewable sources of energy, such as the dual-spiral turbine energy system, is the future of energy generation not simply because fossil fuels are limited in amount, but also because of the clean nature in which the energy is being generated. One must realize the importance of the transfer from old habits to new beginnings to allow for a healthier future for years to come.

Environmental Concerns

Countless inventions, contraptions, and developments today are designed to interact with or be deployed into some sort of water system. There are numerous complications engineers face when designing a new prototype which must be exposed to the ocean, such as buoyancy, stability, pressure, and numerous other factors that vary based on the design’s intentions. However, a key concern that all marine related designs must take into account is that of corrosion and biological fouling.

Corrosion is the act of deterioration on an object, usually caused by a chemical reaction involving acid. Anytime a material is exposed to water for a long period of time, some sort of oxidation or depreciation will occur in or on the material. Salt water contains magnesium ions,
sulfate ions, and hydrogen carbonation ions, all of which tend to attack and wear down almost all materials [16]. Also, there is a high concentration of both hydrogen ions and hydroxide ions in saltwater; thus, making the acidity rather high [17]. The high acidity along with the high concentration of corrosive ions proves seawater to be rather harsh on any submerged vessel or device.

Biological fouling, also known as bio-fouling, is the degradation of an object due to the growth and activity of living organisms [18]. Biological fouling is found in nearly all conditions where water-based liquids come into contact with other materials. Any type of vessel or device that is exposed to ocean water for an extended period of time will begin to accumulate algae, plants, protozoan, crustaceans, and other microorganisms on them. The excessive collecting of these microorganisms will increase the drag on a device, proving to be harmful to any marine related vessel in which streamlines are a primary concern [19].

Although the environmental concerns stated above can have a negative effect on the earth, the benefits of a new, reliable, and clean source of energy far outweigh the negative effects.

Politics

For any sort of advancement in green technology, political support is paramount. Without federal funding, green energy companies would never get off the ground. In its infancy in 2008, the Obama administration promised to increase green energy production. This was largely due to the popular support green energy was receiving over traditional crude oil products, but there was also another incentive for the Obama administration. Green energy is a gateway for an unbelievable amount of new jobs, and with unemployment rates on the rise, any job-creating ventures certainly needed to be explored [20]. Three years later, it seems that the Obama
administration has been true to its word. According to the “Monthly Energy Review” taken by U.S. Energy Information Administration (EIA), renewable energy sources have increased by 27.12 percent since the beginning of the Obama administration [21]. Hydropower in particular has exploded onto the scene, jumping up by 26.28 percent over that time period [21].

**Ethics**

Any time an engineer is on the job, ethics play a key part in everyday decision making. Ethics is basically maintaining a moral obligation when on the job. For an engineer, this is a very broad issue. An engineer must always ensure that safety is the most important part of the project. Not only must engineers ensure that all working conditions are safe, they must also ensure that what is being constructed is safe. Many large corporations choose to cut corners in designs to save money, and it is up to the engineers to draw the line on this issue. Engineers are routinely required to choose whether or not the positives of a project outweigh the negatives. Engineers must not only take into consideration the safety of the project and those working on it, but also what effects could result to the surrounding area where the finished product is located.

The purpose of the dual-spiral turbine design project is to successfully harness energy from ocean currents. Obviously, this energy extraction is the future, with the world slowly moving away from reliance on fossil fuels. However, like any other engineering project, there are certain safety issues that need to be addressed. For this project, potential environmental effects need to be addressed. The ocean is a very fragile ecosystem, and the addition of a turbine to an ecosystem could cause catastrophic effects to the ecosystem. Obviously, engineers working on the project must determine if this project is safe enough to be implemented at all. This project
has an incredible upside, being the production of green energy, but if environmental concerns are not addressed, the project will not succeed.

**Economics**

For all types of renewable energy, economics is one of the largest hurdles to overcome. The start-up costs for renewable energy are daunting to say the least, but the potential for job-creating far outweigh these start-up costs. According to a study done at the University of California, Berkley, renewable energy has the potential to create three to five times more jobs than traditional fossil fuels. [22] The main point of this study was to show that renewable energy jobs are on a first-come, first-serve basis, so cities and states need to take advantage of these opportunities before they are gone. Large companies will eventually take over all energy production, but if a small town were to pull all its resources and establish some kind of renewable energy, they could ensure all the jobs stayed at home.
Designs

Design Requirements

The central objective of the dual-spiral turbine project was to incorporate a streamlined, efficient body design that would generate the largest amount of energy from an ocean current. In order to achieve this goal, many necessary design considerations had to be accounted for. Firstly, in order for the turbine to be successful, it must be able to produce energy from the spinning propellers; thus, the body must have designated space to store one or multiple generators. Therefore, the turbine body should have one or more airtight pressure housings where the generator(s) can reside. These airtight chambers are obligated to withstand the pressure of the seawater at the required depth, based on the location of the ocean current. These pressure housings propose a problem in the sense that the spinning propeller shaft must pass from seawater to an airtight chamber without allowing any water to leak into the chamber. An efficient solution to this problem is to install a shaft-seal around the propeller shaft at the point where the shaft enters the pressure housing, thus keeping all water out of the housing.

Another key design consideration to address was the turbine’s interaction with watercraft and ocean organisms. Many fishing vessels deploy dragnets, which can reach down to potentially far depths. Therefore, the turbine should be deployed in a current where it will not interfere with any shipping lanes or other vessels. Additionally, there are many fish and other marine species which will investigate and interact with the turbine. Thus, the spinning propellers should be tested to see how turbulent and harmful they might be to a passing fish. Also, a device to divert or steer any marine organisms away from the turbine should be looked into. In addition to vessels and organisms, there are many miscellaneous objects floating around the ocean, which the turbine must be able to interact with sufficiently. The turbine’s body must be angled and streamlined in
such a way that any passing seaweed or floating debris will just slide off and pass the turbine body without getting caught on the body or in the propeller.

A further key design aspect, common for any ocean related item, is controlling bio-fouling. Anything which is in contact with ocean water for a prolonged period of time is susceptible to the accumulation of algae or other microorganisms. The buildup of these microorganisms can affect the streamlines and drag on the turbine body, causing a more turbulent flow to pass over the body into the propellers, thus decreasing the efficiency of the propellers. Therefore, the application of antifouling should be looked into in order to mitigate the problem of bio-fouling. Additionally, corrosion is another concern which should be addressed along with bio-fouling. The acidity of ocean water can wear down almost all materials which are exposed to water. Thus, the outer shell of the turbine must be laced with a resin which is not susceptible to ocean corrosion.

Another main design concern to address is the allowance of deploying and retrieving the turbine in the field. The design must be large enough so that an efficient amount of stability and energy production are achievable, but small enough so that deployment is practical. Furthermore, maintenance on the turbine is another concern which should be accounted for. The design should be rather low-maintenance for any underwater work on it would be difficult and timely due to the complications of diving against an ocean current. Therefore, the turbine should not require too much, if any, routine maintenance.

An additional chief design consideration to address is the stability of the turbine’s body when deployed in an ocean current. Major ocean currents can reach speeds exceeding two meters per second. Therefore, the body of the turbine should be able to remain unwavering and stable when exposed to a quick moving flow of water. Also, buoyancy is another attribute which should
be considered on the design. The turbine body must be positively buoyant so that it does not sit on the ocean floor. The turbine will be anchored to the seafloor so that a desired water depth for maximum efficiency can be achieved easily. Thus, the body must be designed with symmetrical air pockets in order to ensure positive buoyancy and proper stability.

Lastly, the most important design aspect on the turbine is having a streamlined body. The major goal of the dual-spiral turbine is to capture the most energy possible from moving water. Therefore, the body must be sleek so that when water passes over and around it, it stays along the curves of the body and does not detach from it. This allows for the largest amount of water flow to be directed to the propellers at the rear of the turbine, generating the most amount of energy.

**Materials for Designs**

To create the models necessary for the preliminary testing of this project, the most logical choice seemed to be to use high density foam. As a large of this foam was readily available through donation, production was easy to begin once the designs were completed. To shape this foam, the four designs being tested were created in Pro Engineer, and then programmed into the CNC machine in the machine shop.
The CNC is a technically-advanced machine that uses a design program known as Mastercam. Basically, the designs created in Pro Engineer are converted to igis files and then loaded into the CNC machine. Now, there are limitations for this machine, chief among them being that the machine cannot cut under the foam. Because the Pro Engineer images are 3-D models with necessary curvature on both sides, the only way to go was to cut the designs in half, and create one half at a time in the CNC machine. Images showing this can be seen later in the design section. Since four designs are being created for testing, the CNC will be required to make eight cuts.

Before the CNC machine can make the cuts necessary, the foam needed to be cut to the appropriate lengths. The CNC machine has certain size restrictions that must be followed for the machine to work properly. For this particular machine, the foam blocks could be no longer than 30 inches and no wider than 16 inches. Of course, this means that the designs must be smaller than these dimensions to be properly cut out in the machine. There is no height restriction in the machine, though of course the foam is only so thick, and for this project stacking, two foam blocks was required to get the appropriate thickness for the models.

![Figure 10. Cutting out the foam with a jigsaw](image)
Because of the size restrictions of the CNC machine, the designs needed to be scaled down in Pro Engineer. The foam was cut into blocks with a length of 24 inches and a width of 16 inches. The sections were traced out on large 4ft by 8ft foam boards, and the foam was cut using a jigsaw. For this part of the project, 16 blocks of foam were required for successful completion of the models.

Figure 11. Foam for CNC being weighted down after it was glued

After the foam was cut out, the issue of the thickness of the foam had to be addressed. The thickness of the design-halves ranged from one to three inches, and the foam was only two inches thick, so the only way to counter this was to stack two foam blocks on top of one another and glue them together. This was done for all eight half-models, to ensure proper cutting for all. The foam blocks were put together using gorilla glue, and then weighted down so to ensure the glue would not expand and make the blocks uneven.
Once the gorilla glue had set up, the foam was taken to the CNC machine, where it was cut into the eight half-designs.

The designs were then cut out of the blocks using a ban saw. Once this was completed, the issue of the thickness of the designs needed to be addressed. Since two block had been stacked together, all the halves of the models were far too thick, and had to be cut down using a hand saw.
Once cut, the models needed to be sanded down. Cutting with the hand saw made uneven cuts, and since the goal was to make the two halves of the model fit together as best as possible, the bottoms of the halves needed to be sanded down. Since it was in an attempt to get a flat surface, a belt sander was used in an attempt to speed up the process. Hand sanding was done over the remainder of the models.

Once this was done, the model halves were ready to be put together. Despite great effort and long hours, the model halves did not fit together very well. To counter this, the most effective method of gluing these models together seemed to be through the use of a very thick adhesive or expanding foam. Since none of the expansion foam tested proved to be adhesive, the only other option seemed to be employing a very thick glue. One option was gorilla glue, which
would expand and fill the crack between the model halves. However, since the models could not be effectively clamped without compromising the structure, there was no way to ensure that the gorilla glue would not expand too much and ruin the model. Thus, finding a glue that was initially thick and did not expand seemed to be the solution, and a viable option was found in Loctite Foamboard Adhesive. Although this method of adhesion seemed to be foolproof, even though it was given ample time to set up (over a week), the adhesive never hardened, and the halves were not solidly together. Thus, it was necessary to pull the halves apart, scrape off the adhesive, and start again. The most likely cause for the model halves failing to stick together was too much space between the models.

![Figure 17. Applying the Loctite Foamboard Adhesive](image)

Since the adhesive attempted was very thick and still failed, basic glues were ruled out. After much discussion, the only other feasible option for binding the halves that emerged was wrapping matting around the edges of the model and fiberglassing the halves together. Although this method was by no means quick or easy, it did somewhat play into the next step of the design process, which was applying a layer of resin to the models. It was much easier to apply the resin while the models were in halves, and three coating were applied. The purpose of this resin being
added was to ensure the overall smoothness of the models. Once the resin was dried, it was easy to wrap the matting around the fiberglassed halves and bind them. This required further sanding of the models, which was tedious to say the least, but came out alright in the end.

![Figure 18. Resining the models](image)

**Generator and Electrical Setup**

This generator was chosen because it had everything needed for underwater, slow current applications. It is small and light weight making it easy to incorporate into the design and versatile because it can fit almost anywhere in the body. The shaft of the generator is stainless steel making it corrosion resistant which is a key element of concern in the harsh underwater environment. Not only is the shaft material ideal but it is pre-threaded making it quite easy to attach the propeller shaft. Other than these external features, the interior design of the generator is also ideal as it is brushless which translates into making it low maintenance and also reduces friction and heat generation. With the generators being contained in a pressure housing with no cooling device, keeping the heat low is very important in low term operation.
As the name suggest, this generator is made to operate in low wind conditions meaning that it should work wonderfully in low water flow conditions as the water is much more dense than air. The body of the generator has built in holes on each side so that it can be easily suspended in the pressure housing. With all of these features in one generator it is as close to perfect as can be found for the purposes needed.

**Flow Dividers**

The main goal of the flow dividers is to direct a majority of the water flow toward the propellers for maximum efficiency. The dividers look like triangles when viewed from above, with the point facing into the current; they are intended to be located in the center and at the rear of the body. The idea is that the dividers will divert the water flow both directions towards each propeller, which theoretically should increase the amount of energy generated. Additionally, the flow dividers can also be raised up vertically so that they act as a fin, increasing the transverse stability of the turbine.
One other point that should be noted is the Power Equation:

\[ P = (C_p)(0.5)(\rho)(A)(V^3), \]

Where \( P \) = power, \( \rho \) = density of water (1025kg/m\(^3\) for sea water), \( A \) = sweep area of the turbine (in m\(^2\)), and \( V^3 \) = velocity cubed. [24]

It is important to note this equation because it underlines the purpose of the flow dividers. As noted by the velocity cubed term in the equation, it is clear to see that even a small increase in the velocity of the flow as it flows into the propeller will have an incredible effect on the power generated by the turbine.
Body Design Ideas

Design Criteria

The key focus of the T.U.R.T.L.E.S. team was to design and fabricate the most efficient turbine body in order to harness the maximum amount of power from an ocean current. It was decided that numerous model designs were to be fabricated and tested in order to narrow them down to the optimum body shape. There was a specific criteria used when designing the models. Firstly, the models must have a smooth shape so that no floating objects, such as seaweed, get snagged or caught on the body. If objects were to get caught on the body they would disrupt the flow, lowering the efficiency of the turbine. Secondly, the body designs need to be thick enough to house two generators, one for each propeller. Also, the models should have a wide enough rear so that the propeller can be oriented in a manor where they do not interfere with each other. Additionally, the models must be designed so that they are stable when exposed to a water flow of about two meters per second. Lastly and most importantly, the body designs must have minimal drag and superb streamlines. Four model designs were created based on the criteria; each of them had a specific motivation that they were influenced by. The names of the four designs are the Arrowhead, the Teardrop, the Concorde, and the Shield; the names correlate with what the models look like as well as what they were influenced by.

Arrowhead Design

The Arrowhead design is based off of an aircraft vehicle called the Hypersonic Technology Vehicle 2. This aircraft was designed specifically for high speeds, its superb aerodynamic properties allow it to reach velocities above 13,000 miles per hour. Similar to the
Hypersonic aircraft, the Arrowhead is designed to be a sleek, streamlined shape with minimal drag.

Figure 21. Arrowhead Pro-E drawing

Another important aspect of this design is the overall smoothness of it. This undeviating shape should ensure that no seaweed or other drifting debris gets caught on the body while it operates in the water. Also, the width-to-height ratio of the model should allow it to remain stable when being acted on by an ocean current.

Figure 22. Top half of the Arrowhead design after it has been cut out by the CNC machine.
The wide body design allows ample room at the rear of the model for the two propellers to be installed so that they do not disturb each other. Additionally, the thickness of the body design supplies a generous amount of space for two generators to be installed inside a pressure housing.

Figure 23. Arrowhead after it has been resined and fiberglassed.

Teardrop Design

The Teardrop design idea is simply based on the most streamlined structure in science, a teardrop. The body is designed so that the wider, more blunt end faces into the ocean current, allowing the streamlines to flow around the body and remain attached to the surface until reaching the propellers.

Figure 24. Teardrop Pro-E drawing
When water flows around a cylinder, boundary layers form on the rear side of the object due to the detachment points at about positive sixty degrees and negative sixty degrees from the center of the contact point on the cylinder.

Figure 25. Top half of the Teardrop design after it has been cut out by the CNC machine.

These boundary layers that form are basically air pockets where little to no water flows through; therefore, if the propellers were located at these spots, almost no energy would be generated. Thus, the Teardrop shape allows the water flow to run smoothly along all its surfaces, causing no boundary layers to occur. Therefore, the Teardrop design permits an efficient amount of water flow to reach and power the propellers at the rear of the turbine; thus, producing a significant amount of energy.

Figure 26. Teardrop after it has been resined and fiberglassed.
The wide body design supplies plenty of room for the propellers to be installed and for the generators to be housed comfortably.

**Shield Design**

The Shield design looks like a shield when viewed from above, where the point or base of the shield is pointed into the ocean current and the rounded, blunt side is the rear where the propellers attach.

![Figure 27. Shield Pro-E drawing](image)

There are two smooth, symmetrical humps running longitudinally with the design; these pods are where the generators will be stored in airtight pressure chambers. In addition, these pods will create a sort of funnel system down the center of the body, directing an efficient flow of water toward the propellers.
Figure 28. Top half of the Shield design after it has been cut out by the CNC machine.

Also, the fact that the point of the shield shaped body is facing into the current, any seaweed or other floating debris should flow outwardly away from the propellers as it moves along the body, thus preventing any snagging or clogging.

Additionally, the design has wing-like supporters on both sides of the body which should add stability to the turbine when placed in a fast moving flow of water.

Figure 29. Shield after it has been resined and fiberglassed.
Concorde Design

The Concorde body design is based off of the Concorde Jet, a supersonic airliner built for speed and minimal drag. The jet could reach speeds above 1,300 miles per hour, making it the fastest passenger aircraft ever to be used. However the supersonic jet was discontinued in 2003 because its extraordinary speeds made it too difficult for pilots to control the aircraft. The Concorde Jet’s superb aerodynamic properties made it an appealing inspiration for a turbine body; the Concorde model is designed to have minimal drag and exceptional hydrodynamic properties.

![Figure 30. Concorde Pro-E drawing](image)

When looking at the Concorde model, it is easy to see why it is such a captivating turbine body design. Not only does the overall shape of the body seem to indicate a very smooth motion through the water, but also the lack of edges on the body should ensure no foreign objects, such as seaweed or debris, get caught on the body.
Another important aspect of this design is the wings. Not only are they exceptionally streamlined, they should also ensure sufficient stability of the model. Also, the wings supply the model with a wide rear, allowing two propellers to be installed far enough apart so that they do not disrupt each other.

The Concorde model is designed to house two generators in a central pressure housing. Specific details about the generators and the pressure housing can be noted in the Generator section above.

Figure 29. Top half of the Concorde design after it has been cut out by the CNC machine.

Figure 25. Concorde after it has been resined and fiberglassed.
Model Testing

Wave Tank Testing

Purpose

The purpose of testing in the wave tank was twofold; to test for the drag coefficients of the models as they go through the water, and to test for the overall stability of the models. After considering several options, the wave tank on the Florida Tech campus emerged as the most feasible location to do this testing. This was due to the fact that one can control the exact conditions occurring in the tank, which should help to ensure accurate results. A pulley system was used to test for the drag coefficient of the models, with several trials being run to ensure accurate results. To find the stability of the models, the simplest way was to videotape the trials of the models, and observe their movements as they were pulled through the water. If possible, finding a sufficient current to anchor the models in would be even better.

Theory

For both tests in the wave tank, buoyancy was a major issue. The models are made of high-density foam with a fiberglass coating, so they are very positively buoyant. However, for the two tests to be effective, the models needed to be neutrally buoyant. To accommodate these conditions, weight needed to be added to the models. Because so much weight was going to be necessary, using lead seemed to be the most logical choice, as it was one of the densest materials readily available. A calculation was derived to determine how much lead was necessary to ensure neutral buoyancy;
where $V_{\text{lead}}$ = volume of lead to be added, $V_{\text{model}}$ = volume of model, $\rho_{\text{foam}}$ = density of foam, $\rho_{H2O}$ = density of water in tank, and $\rho_{\text{lead}}$ = density of lead

All the values for how much lead was necessary can be seen in Table 1 the data section. Due to the large gap between the models, rather than seal the model completely and allow it to be filled with air, a corner was left open to allow the space between the halves of the model to fill with water instead of air. Once the models were stable below the waterline, the testing could begin.

When determining a way to find the drag coefficient of the models, a fairly basic concept was devised, using the equation for drag force:

$$C_d = \frac{2F_d}{\rho V^2 A}$$

where $C_d$ is the drag coefficient, $\rho$=density of water (1025kg/m$^3$ for sea water), $A$=reference area of the model body (in m$^2$), $V^2$= velocity squared, and $F_D$ is the drag force. [25]

When one looks at the equation for drag force, one can see that it is easy to find all the variables except for the drag coefficient and that can be solved once all the other variables are determined. Now, this equation did have a slight difficulty, the reference area. Research showed that some believe that the reference area is just the frontal area of the models, while other feel that the entire surface area of the model should be taken into account. To avoid conflict, the easiest method seemed to be getting values for every possible method, so that anyone observing the data could have access the results they were looking for. To find the total surface area of the models, Creo Pro-Engineer was utilized. This program was also used to find the frontal area by
changing the view of the model to only a frontal-view. However, to ensure accuracy, another test to find the frontal area was performed; the shadow test. This test seemed necessary because the models were not exactly the same area as those in Pro-Engineer, due to difficulties incurred during fabrication. Although they are based on the designs created in Pro-Engineer, imperfect cutting of the bottoms of the models with the saw/sanding belt rendered the models imprecise to the Pro-Engineer designs. To perform the shadow test, one simply mounts the model in a box, shines a flashlight onto the model (creating a shadow behind it), then traces the shadow. The reason for the box is that magnification of the shadow needs to be taken into account. It is easy to determine the area of the box and the shadow of the box using a measuring tape, and thus the magnification can be determined. Figure 33 shows this method in action.

Figure 33. Tracing the shadows of the models onto cardboard

Once the models have all been traced, they had to be cut out of the material they were traced on. Cardboard worked very well for this test, as it is both strong and thin. Each of the pieces was cut out and weighed. Another piece of cardboard was cut out, this one in a square shape with known dimensions. It too was weighed, and from this the cardboard's weight per unit volume (density) was determined. However, since the same material (with a uniform thickness) was being used for both the control body (the square) and the test bodies (the models), it was
really a weight per unit area that was determined. This was very useful, since there is now a
known weight per area and a known weight for the models, so using the known ratio allows one
to find the area of each of the models.

For determining the stability of the models, the best method of testing appears to be
seeing exactly how the models react with a current flowing around them. When determining the
stability of a body in water, there are six types of motions that need to be taken into account. The
first three are all types of translation, whether that be forward and backward (heave), side to side
(sway), or up and down (heave). The other three are rotational motions, including forward and
backward (pitch), side to side on the longitudinal axis (roll), or tailing out on the vertical axis
(yaw). [26] As the models are being pulled through the water, it is highly unlikely that they will
stay perfectly straight. More likely, they will display one or more of these motions, and the one
that the displays the fewest of these motions will be deemed the most stable.

Ideally, the most effective method for testing stability would have been to put the models
into a current, and let the water flow over them. However, although many attempts were made to
accommodate this method, all failed. First, all the rivers in the area were observed to see if any
generated a current strong enough for testing, but none did. After that, the next option was to
attempt to get permission to test in a “lazy river” like those found at resorts and water parks.
However, none were available for testing. The last option was to create a pump system that
would generate a current through the wave tank. A system involving PVC pipe going under the
tank was the first option, but neither of the motors that were attached were anywhere close to
powerful enough, so the final effort came with the renting of a four horse centrifugal pump with
a three inch diameter hose. The hoses were both 20ft long, and they generated a much stronger
current, but it was still not powerful enough to be an effective method of testing.
Figure 34. The pump system used in an attempt to create a current

**Apparatus**

For determining the drag on the models, the most logical test seems to be using a pulley system. As shown in Figure 36, this is a pulley system in which one pulley sits stationary below the waterline acting as a guide while the other is high above the tank. Each of the models was harnessed with fishing line, to allow for equal distribution of force throughout the model as it was pulled through the water. Figure 35 shows an example of a harnessed model.

Figure 35. An example of a harness on a model

The harnessed model is attached to a line, which wraps around both pulleys. Attached to the other end of the line is a hook, where a certain amount of weight is attached, enough to pull the model across the tank. The pulley in the water is necessary for this experiment because if it was not included, the model would be pulled up out of the water by the pulley positioned above the tank. The tank itself provides a limitation for how large the models can be, as it is only about...
two feet wide. However, the CNC machine cannot cut anything wider than 15in, so this was not an issue. In fact, the models were an appropriate size for the tank because they definitely needed some room to maneuver as they were pulled through the wave tank.

![Pulley system design](image)

Figure 36. The pulley system design to be used in this test. The Guide is on the right.

**Procedure**

1. Once the pulley system had been constructed and the necessary weight had been added to each model, the first step of the drag test was to create a harness for each model, using monofilament fishing line and glue. After harnessing the models, the first model tested was the Concorde. An 8ft distance was marked on the tank as the test section.**

2. The harness on the Concorde was attached to the line in the pulley system via a key-chain ring, to allow for easy attachment and removal once the testing of the model is done.
3. A weight of 500g was attached to a line at the end of the pulley. The weight was lifted 11 feet off the ground, and then dropped, pulling the model across the tank.

4. There needed to be five good trials performed at this weight. A good trial was indicated when the model did not hit the sides or bottom of the tank, or break the surface of the water. The timing of the trial must also be accurate for the trial to be deemed a good one (two timers with results within 0.1 seconds of one another).

5. Once five good trials had been recorded, the weight at the end of the pulley was changed to 750 grams.

6. Again, five good trials needed to be recorded at this weight.

7. Finally, the weight at the end of the pulley was changed to 1000g, and five good trials had to be recorded.

8. Steps 2-7 had to be repeated for the Teardrop, Arrowhead, and Shield to complete the drag test.

**NOTE: For the shield test, the testing section needed to be reduced to 6ft to allow for accurate trials.

Figure 37. Testing in progress
Results

Table 1: Amount of lead necessary to make the models neutrally buoyant.

<table>
<thead>
<tr>
<th>Model</th>
<th>Calculated weight to be added (g)</th>
<th>Weight from water (g)</th>
<th>Necessary extra weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrowhead Half 1</td>
<td>903.3</td>
<td>646.9</td>
<td>332</td>
</tr>
<tr>
<td>Arrowhead Half 2</td>
<td>847.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concorde Half 1</td>
<td>550.4</td>
<td>312.9</td>
<td>185.7</td>
</tr>
<tr>
<td>Concorde Half 2</td>
<td>609.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield Half 1</td>
<td>616.7</td>
<td>414.1</td>
<td>246.1</td>
</tr>
<tr>
<td>Shield Half 2</td>
<td>901.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teardrop Half 1</td>
<td>927.8</td>
<td>409.2</td>
<td>122.9</td>
</tr>
<tr>
<td>Teardrop Half 2</td>
<td>967.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: The Drag Coefficients and Standard Deviations for the different areas used during the drag test.

<table>
<thead>
<tr>
<th>Model</th>
<th>Projection Area</th>
<th>Total Area from Pro-E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drag Coefficient</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Arrowhead</td>
<td>0.404</td>
<td>0.012</td>
</tr>
<tr>
<td>Concorde</td>
<td>0.641</td>
<td>0.023</td>
</tr>
<tr>
<td>Shield</td>
<td>0.943</td>
<td>0.028</td>
</tr>
<tr>
<td>Teardrop</td>
<td>0.431</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Discussion - Drag Test

The purpose of the drag test was to find out which model had the smallest drag coefficient. Having a small drag coefficient would indicate that the model has very little drag on it when in the water. Any drag on the model would decrease its efficiency, so the less drag, the better. Research showed that there was some discrepancy about which reference area to use when calculating the drag coefficient from the drag force equation, so both areas were used, and the two results are displayed in Table 2. As one can see, the Arrowhead produced the smallest
drag coefficient for both areas, even though that value differed greatly between the two areas. This was not really an issue, as this test was to compare the models against each other, and the Arrowhead was consistently the best. The Shield was the worst for both tests, while Concorde and Teardrop switched spots between tests. For these two, it just depends on one’s preference about which area to use; deciding that will reveal which of the models has a better drag coefficient.

As can be clearly view in Appendix B, a total of 60 trials were recorded. However, far more than 60 trials were run. As stated before, a trial was only recorded if it was a “good” trial, which is to say that the model did not hit the sides or the bottom of the tank, or break the surface of the water. Some of the models, such as the Teardrop, were very easy to test, with almost no bad trials. Other models, such as the Shield, took at least four trials to get one good one. Where and how the model was released was crucial to the success of the run. So all in all, it probably took 200 to 250 trials to get 60 good ones.

Error Analysis for Drag Test

Problem: Different turbidity of the water as a result of failing to let the water settle between each test.

Solution: The ocean does not have a consistent flow. Also, the water was allowed to settle while the weights/models were changed out. This is why five trials were run for each weight, and 15 total per model.

Problem: Accurately timing the trials.

Solution: Two timers were being used for each test. Since both timers were members of the
group, a certain amount of human error was involved. To counter this, a trial was only considered acceptable if the two times were no more than 0.1 seconds apart (both timing devices went to 0.01 seconds).

**Problem:** Taking proper measurements (dimensions of the tank, mass of the weights used during the trials).

**Solution:** Two people measured the tank to double-check the dimensions. As for the scale, proper calibration of the scale was ensured by weighing something with a known weight for comparison. Also, the same scale was used for all the measurements for the test, so even if there was a problem with the scales, it would have been a systematic error (which is to say, all the measurements in the experiment would have been altered the same amount), and thus not caused any issues with the experiment.

**Problem:** The guide controlling the pulley system wobbled quite a bit during a dry run.

**Solution:** Four clamps were binding the guide to the tank as tightly as possible, allowing virtually no movement whatsoever. These clamps were checked during testing to ensure that they remained tight.

**Problem:** Poor construction of the models - most notably, bubbles formed on some of the models after resin had been applied.

**Solution:** For the overall construction of the modes, copious amounts of sanding was done to attempt to ensure the models were as smooth as possible. As for the bubbles, it is still as mystery as to why they formed, but to attempt to remove them, a very fine sand paper was applied to the
prolonged at the problematic areas.

**Problem:** Air pockets in the models causing free-surface effect.

**Solution:** When the models were being tested, they were initially held under water for several minutes, allowing any trapped air bubbles to escape and be replaced by water.

**Discussion - Stability Test**

The purpose of the stability test was to determine which of the models was the most stable in the water. Using the various ship-motions described in the theory section, each of the models was reviewed and rated for how well they did. It was important to note how the models behaved at various weights, as some did better at higher weights, while others did worse. Of the models tested, the Concorde was the most stable. Other than a slight yaw at the end of its runs, it was close to perfect. The next best was the Arrowhead, which was pitched downwards for all of its runs. It also displayed a fairly intense oscillation to further underline the pitching motion. With this model, however, it is fair to argue that an uneven distribution of weight may have been the cause of the pitching. The model was clearly nose-heavy, and if this had not been the case the model may have performed better. The Teardrop design had similar results to the arrowhead. Again, uneven weighting may have been to blame for some of the stability issues of this model. Throughout all the testing trials, the Teardrop was consistently rolled to the right. At 500g, the model was severely pitched downward. However, the pitch was not as bad at 750g, and even better at 1000g. There was also a noticeable oscillation at 750g, but it too had improved at 1000g. Thus, the faster the Teardrop went, the better it performed. Finally, the Shield was the most unstable of the models tested. Throughout the trials, the Shield displayed severe pitching and swaying. In fact, it was so bad that the test section needed to be shortened to 6ft instead of
8ft to get a good trial in before the model struck the walls of the tank. Unlike the Teardrop, the Shield actually performed better at 500g than at 1000g, showing that at lower velocities the model was more stable.

**Error Analysis for Stability Test**

**Problem:** Limits of the human eye, considering this test was strictly visual observations.

**Solution:** All trials were videotaped, so they could be viewed later to observe any issues with stability.

**Problem:** Properly identifying what type of stability issues were evident in each trial.

**Solution:** It was important to ensure proper understanding of different types of stability issues before reviewing the tape. Once these issues were properly defined, a successful review was possible.

**Problem:** Poor construction of the models - most notably, bubbles formed on some of the models after resin had been applied.

**Solution:** For the overall construction of the modes, copious amounts of sanding was done to attempt to ensure the models were as smooth as possible. As for the bubbles, it is still as mystery as to why they formed, but to attempt to remove them, a very fine sand paper was applied to the problematic areas.

**Problem:** Air pockets in the models causing free-surface effect.

**Solution:** When the models were being tested, they were initially held under water for several
minutes, allowing any trapped air bubbles to escape and be replaced by water.

**Conclusion**

The drag test was designed to reveal which of the models would have the lowest drag as it moved through the water. Of the models tested, the Arrowhead proved that it had the lowest drag when pulled through the wave tank. As for the stability test, the Concorde proved to be the most stable out of all the models tested. The Arrowhead was clearly second best, and it is reasonable to conclude that had the weights in the model been better distributed, perhaps the Arrowhead would have performed better. Overall, it seems that the wave tank test has given the Arrowhead and the Concorde the early advantage, while the wind tunnel and Fluent will determine which models are the best.

**Wind Tunnel Testing**

**Purpose**

The purpose of testing in the wind tunnel was to determine the streamline flow over the various model designs. The reason that this testing was necessary stems from the principal idea of flow-detachment points over bodies. As four very different body shapes were being tested, some theoretically will have more detachment points than others, and the ideal design would have as few detachment points as possible. This experiment will prove which design has the most streamlined body.

**Theory**
For this experiment, a calculation for similitude was necessary for the change of the density of air to the density of water. As previously stated, the ideal speed at which the turbine will operate is about 2m/s. However, this velocity is in water, and when converted to air, a velocity of approximately 65m/s is necessary to have accurate similitude. However, this cannot be duplicated in this test, as the wind tunnel being used only runs up to around 25m/s. Even so, this experiment should still produce fairly accurate results. This is due to the fact that the streamlines over the bodies really will not change very much once going at such high speeds anyway. Also, it is important to remember that the similitude calculation is itself an estimate, so even if it was possible to get the wind tunnel to the desired speeds, the results would still only be as accurate as the similitude. Below is the formula for calculating similitude:

\[
\frac{V_m L_m}{V_m} = \frac{V_p L_p}{V_p}, \text{ where } V \text{ is velocity, } L \text{ is length, and } v \text{ is kinematic viscosity (model/prototype)}
\]

To perform this experiment, the “thread method” seemed to make the most sense. The purpose of the thread method is to clearly illustrate the streamlines over a body. Long pieces of thread are attached all over the model, and when the wind tunnel is turned on, the wind will push the thread pieces over the models, showing where the streamlines are located. This method will reveal any detachment points on the model (anywhere the thread is flying around rather than holding tight to the model is a detachment point).

Apparatus

This experiment will be carried out in the wind tunnel located at the Florida Tech machine shop. It is important to note that the size of the testing area had to be taken into account before the models could be designed. The dimensions of the testing section were 48in long by
21in wide by 21in high. The length and height were not going to be an issue, but it was important to be conscious of the width. Not only did the models have to be smaller than 21in, but in order to avoid wall-effects from the side-walls, there needed to be at least three inches of space on each side of the model. This meant that the model could not be more than 15in wide. Since this correlated perfectly with the limitations of the CNC machine, this was easy to accommodate.

![Figure 38. Testing in progress](image)

**Procedure – Wind Tunnel Test**

1. The procedure for all the models was exactly the same. The first model tested was the Concorde.

2. The first step was to attach threads (using tape) all over the top half of the Concorde, focusing on the front and sides of the model.

3. The Concorde was then placed in the wind tunnel located in the machine shop at the Florida Institute of Technology.

4. The wind tunnel was then turned on. Similitude calculation from before indicated necessary wind speeds greater than the abilities of the wind tunnel, the most logical way to go was to observe the behavior of the threads at different wind speeds.
5. The wind tunnel was set so that it produced speeds of 5m/s. The behavior of the threads was observed and recorded via a camera.

6. Step five was repeated at wind speeds of increasing all the way to 20m/s.

7. As noted before, steps 2-6 were repeated for the Teardrop, Arrowhead, and Shield.

Results

![Figure 39. Models undergoing the thread test](image)

*Videos of the testing reveal the purpose. The pictures just show the attached threads.*

Discussion

The purpose of the wind tunnel test was to determine how well streamlined each of the models was. This test was performed using the thread test described in the theory section, and some interesting results were attained. Firstly, it is important to note that the wind was only blowing over the top half of the model, while the bottom was sitting on the floor of the test section. It was advised by the wind-tunnel administrator that this would cause problems off the backs of each of the models, which turned out to be an accurate statement. Also, each of the
models had one back corner that was unsealed to allow water into the model during the drag test. Unfortunately, when in the wind tunnel, his hole created a suction effect, causing all the threads attached around the holes to be sucked inside them. Thus, it was impossible to determine the actual streamlines at the corner. In terms of which model was the best, the Arrowhead was the most impressive. The main face of the Arrowhead (the top and sides) were about as good as they could be, with no discernible detachment points. The only problem came on the down-slope at the back of the model, but the detachment points here were fairly minimal. The next best model was the Concorde, which was overall pretty good. There were a few miscellaneous detachment points on the sides and the back, but nothing too terrible. The only cause for concern with this model was a small turbulent zone just beyond the start of the wing. This may have been a flaw in the design, as the turbulent zone was in the exact same spot on both sides of the model. The Shield comes next, and in a word, it was very inconsistent. There were many detachment points along both bumps on the model, but they were scattered in some spots and dense in others. There was no really good or really bad areas, just inconsistent throughout the whole model. Finally, there was the Teardrop, which was just plain bad. There were detachment points all along the side, and that was just the start. At the front of the model, the threads seemed to hold at first, but as they wrapped over the edge, they began to detach. Finally, there were detachment points along the flat part of the model, which simply underlined the fact that the streamlines on this model were terrible.

**Error Analysis for Wind Tunnel Test**

**Problem:** Wall effects from the sides of the tank causing interference with the streamlines.

**Solution:** According to the wind tunnel operator, as long as at least two inches of space was left
on each side of the model, the wall effects should not be a problem. None of the models tested had less than three inches of space on each side of the model.

**Problem:** Wind effects causing models to wobble as the wind currents move over them.

**Solution:** On their own, the models are heavy enough to stay in one spot. However, some of the models do not have a flat base, and thus cannot remain stable in the wind tunnel. To fix this problem, small pieces of lead left over from the drag test were placed into the wind tunnel and wedged beneath the models to hold them in place.

**Problem:** Overlapping threads causing inaccurate results.

**Solution:** When taping the threads onto the model, great care was taken into avoiding overlap. The threads were stretched to their limit, and the next thread was attached just beyond the reach of the previous thread.

**Problem:** Poor construction of the models - most notably, bubbles formed on some of the models after resin had been applied.

**Solution:** For the overall construction of the modes, copious amounts of sanding was done to attempt to ensure the models were as smooth as possible. As for the bubbles, it is still as mystery as to why they formed, but to attempt to remove them, a very fine sand paper was applied to the problematic areas.

**Problem:** An open hole in the back corner of each of the models. It was essential for the drag test.

**Solution:** Since this fault was consistent throughout all the models, it was advised by the wind
tunnel administrator to not put much faith into the results in the area immediately surrounding the hole. However, the rest of the model would not be effected by this fault.

**Conclusion**

The wind tunnel test was meant to reveal which of the models had the best streamlines. Using the thread test, it was determined that the Arrowhead was the best, with the Concorde coming in a close second. The results of the Arrowhead were just staggering, with nearly all the threads lying perfectly flat along the body even at high wind speeds. Like the drag test, this test showed the Arrowhead and the Concorde to be the best models. Perhaps Fluent will be able to generate a clear winner. Otherwise, the best course of action may be to combine the models to create a model better than either of them.

**Fluent Testing**

**Theory**

Gambit is a geometry and mesh generation software, usually used with Fluent. A mesh is basically a volume broken up into smaller cells, making it easier for the Fluent solver to estimate what is occurring in the fluid on a cell by cell basis, rather than trying to solve a volume all at once. For the purposes of this project, it was used only for mesh generation. The geometry was made in Pro-Engineer and imported into gambit as an .igs file. It was oriented so that the front of the model is pointing in the negative x-direction, which made fluent analysis easier, as the default flow in Fluent comes from this direction. Once in Gambit and correctly positioned, a box was made around the model with dimensions of 400x200x200 inches. The models themselves
are only around 15-18 inches long depending on the model, and the box needed to be much bigger, so that the flow over the bodies is not affected by the sides of the box. The two volumes, the box and the model, then need to be spliced, meaning that the shape of the model will then be cut out of the box and the model volume itself will be removed. What’s left now is a single volume, which will be defined as a fluid, and will be more detailed in the Fluent part of the simulation. Now comes the actual mesh generation, which takes place in several steps. First, the walls of the volume have to mesh before the entire volume can be done. The walls are meshed with a setting known as Tri-Pave, meaning that the mesh will be composed of triangles. Other options exist, such as quad-pave, which generally yields a more accurate result. However, this could not be done with the complicated surface of the model. The next step is the volume meshing. This can take quite a while, depending on how fine the mesh needs to be, as well as how complicated the shape of the volume is. This process took about thirty minutes per model. Once this process was complete, the mesh itself is done, but working with GAMBIT is not. The volume walls need to be declared, with the front, sides, top, and bottom walls being declared as velocity inlets. The back wall had to be defined as an outlet. The volume cut-out where the model also needed to be defined as a wall, so Fluent would know to generate flow over the model, and not through it. The mesh can then be examined to see how good the cells are using a few different rating systems, the most important of which is equi-angle skew, which rating based on the angles inside the triangular cells. The more equilateral the triangle is, the better the rating. In some cases the angles are so bad that the results yielded in Fluent are not even considered useable, and in extreme cases the mesh may even be unsolvable. With inspection done, at this point the mesh is then exported into Fluent as a .msh file.
When Fluent is opened, it is imperative that the 3D option is selected, so that it reads the mesh correctly. With all settings correct, the mesh can then be imported. Once imported into Fluent, the mesh should be checked before anything is done. This is accomplished by simply clicking the “Check Mesh” button that is under general settings. As long as the mesh was made correctly, this should all check out, and the Fluent solver settings can then be selected. The fluid default is air, so that needs to be changed to water to suit the purposes of the project. The physical properties, such as density, temperature and viscosity of the water, can also be altered to suit fresh, salt, or any other type of water. The type of flow also needs to be specified, such as laminar or turbulent. In all cases, a laminar flow was used because the criteria and specifications needed to simulate a turbulent flow are very complicated. Next the initial velocity needs to be set, which was 2m/s in the x-direction for these cases, as that is approximately the top speed of the gulf stream, where the full-scale version of these models would theoretically be deployed. Monitors are the next step and these specify what Fluent will solve for, and the options are endless, but the only one set up in these tests was a fluid velocity magnitude sensor. The last step is to initialize the flow from the inlet, which lets Fluent know that it is the starting point of the flow. The calculations were then run, doing 50 iterations. When the calculations were finished, the animations could be seen. All the animations are in the results section. Fluent offers a few different animations, including vectors and particle tracking, but path lines was the one used in the images that can be seen. The path lines are color coded and come with a color scale on the side so that the velocity off the back of the model can be found. This is where it counts as this is where the turbines will be.

Results
It was impossible to run the simulation for the shield trial, which will be addressed later.

Discussion
The purpose of performing the Fluent computational analysis was to observe the streamline flow over the various bodies. One major point to note about the simulations pictured above is that they are not completely accurate. Because of the free surface effect, which is automatically applied in Fluent, it appears there is no flow over the bodies. This, of course, is not the case, but the only part of the images that applies to this project is at the end of the models, which is clearly visible.

To rank the models, all the velocities at the back of the model need to be observed. The only relevant velocities are the ones directly off the backs of the models. Beyond that, the results do not matter. According to the results, the Concorde was the best, with a maximum velocity of 1.69m/s off the back. This was a very impressive result, considering the original flow was just 2m/s. The other results were not nearly as impressive. The Arrowhead produced a maximum velocity of 1.36m/s, while the Teardrop only managed a velocity of 1.13m/s.

There were no results for the Shield model. This was due to the fact that the curvature of the model generated in Pro-Engineer was so complex, the volumes created would not mesh. Thus, fluent failed to generate any adequate results. However, since the Shield had done so poorly in the earlier tests, it had already been ruled out as a model that would be continued upon, so there was no cause for concern about its failed meshing.

Conclusion

According to Fluent, the Concorde had the best streamlines of the models tested. Although this did not exactly match up with the wind tunnel results, which deemed the Arrowhead the most streamlined. However, this is why two tests were run, so that more data could be considered.
Conclusion – Overall analysis of the models based on all the testing

At the end of each test, each of the models was ranked based on how well they did during test. Once all the tests were concluded, the two best models were obvious choices. The best model was the Arrowhead, while the Concorde finished a close second. The next step is to take these two models and improve them. Four new models are going to be created based on these two models, and subjected to the same testing. Once the final test has been completed, the best body design will be revealed.

Updated Designs

Fabrication of Updated Designs

The final analysis of the testing concluded that the Arrowhead is the best out of the four models, while the Concorde is a close runner-up. It was decided that four new models would be designed based off the Arrowhead and Concorde in an attempt to improve the bodies. The new models would perform the same exact tests that the old models were subjected to in order to compare results. It was also decided that due to time constraints, the fabrication process of the new models needed to be revised. After careful consideration, some new methods were implemented to make the models far more accurate.

The CNC machine can only cut out half-models, and must leave some room at the bottom, so that the drill bit does not strike the bed of the machine. Because of this, a certain amount of extra foam was on the bottom of the model halves, and needed to be removed. For the original models, a hand saw was used to cut off the excess foam. However, the cuts were inadequate, so a belt sander was used to smooth out the uneven surfaces. Even though this made the models much smoother, none of them fit well together because it was impossible to tell how
much sanding had been done, not to mention the halves of the foam were deformed slightly
because of the pressure of the sanding belt. Therefore, for the new models, a shelling tool was
implemented.

![Figure 43. Models being cut out with the shelling tool](image)

This is a small rotary tool that attaches to a mill and drills down into the foam. As seen
in figure 43, the blades go approximately ¼ in into the foam with each cut, with the ruler on the
mill showing how far the blades are going. The desired thickness of the halves was found from
Pro-Engineer, and the models were cut down until they reached the desired thickness. While in
the mill, the models were clamped tightly down and a level was used to ensure they remained
perfectly flat. The results of using the shelling tool on the mill machine proved to be a significant
improvement in the fabrication process.

Similar to the original models, the new models were far too buoyant for testing. Thus,
lead had to be added to them. In the first round of testing, lead blocks were acquired from a local
scrap yard, and then cut in the machine shop. The blocks were very difficult to cut, however,
causing many of the “blocks” to be unevenly cut, making finding their exact density very
difficult. For the new models, another block of lead was acquired from the scrap yard, but this
time, instead of the lead being cut, it was melted down. A rectangular mold made of aluminum
was constructed, and the molten lead was poured into the mold. After it cooled for a few
minutes, water was poured onto the lead, hardening it. Then it was knocked out of the mold ready for use. In the end, twelve blocks of the same size were constructed. As they were rectangles, it was much easier to put exactly the appropriate amount of lead where it was needed. Also, when the lead was just small rectangles, it was far easier to cut than before.

![Figure 44 Aluminum mold for the lead blocks](image1)
![Figure 45 The lead blocks in the models](image2)

To ensure accurate testing, the models needed to be as smooth as possible. The original models had several layers of resin applied to them to ensure their smoothness. However, although this was mostly effective, some unexpected complications arose. Due to the drastic curves on the models, especially the Shield, the resin began to pool so that it was thick in some spots and thin in others. There was no real way to control this issue. Also, on some of the models, air bubbles formed. At first, more resin was added in an attempt to cover them, but that failed. The next option was sanding down the bubbles. However, some of them went all the way to the foam, and could not be sanded. Since the source of this problem could not be pinpointed, the best option was to avoid it all together. Thus, several layers of gelcoat were applied to the new models to ensure their smoothness. Once the last layer of gelcoat was dry, the models were wet-sanded until they were as smooth as glass.
Finally comes attaching the two halves of the model together to complete the model. As noted previously, the original models had large gaps between the two halves when put together. Thus, the only feasible way to put them together was by wrapping matting around the sides and fiberglassing them together. This method was very tedious, for the models had to be heavily sanded once the models were dry. However, the new models halves were lying almost perfectly flat on one another. This allowed many more options for adhesion, and the first option was to apply a thick layer of Loctite spray-on glue to the bottoms of the halves, and stick them together. Initially, this method seemed to work, but over time it became clear that the glue was not strong enough. Thus, during the gelcoating procedure, a thin layer of Bondo was applied to the models. As seen in figure 47, the Bondo was forced into the cracks around the edge of the model, allowed to dry, and then sanded over. Another layer of gelcoat was applied over the Bondo to ensure smoothness over the entire model.
Body Design Ideas - New & Improved

Flat-Back Design

The Flat-Back model is solely based off of the Arrowhead body design. It was observed in the wind-tunnel test that the cavity or dip at the rear of the Arrowhead design proved to cause a pressure pocket and some slight disturbances behind the model. In order to solve this issue, the cavity is simply removed, resulting in a flat back on the new model, which is why this design is named the Flat-Back.

This body design is the same as the Arrowhead in all other aspects, therefore it still satisfies all of the original design criteria, such as: enough room for two propellers and two generators, small wings for stability, and a smooth shape to prevent snagging and for allowing
minimal drag.

**Lava Lamp Design**

The Lava Lamp model is also an alteration of the Arrowhead’s body design. Just like the Flat-Back, the cavity was replaced; however, in this case it is replaced with a cone-tail that extends off of the rear of the model while tapering down to a smaller radius.

![Figure 49. The Lava Lamp in Pro-E and finalized](image)

The inspiration for this revision is found in nature; numerous animals are equipped with tails to aid them in balance and stability. Therefore, the addition of a cone-tail off the back of this design is to help improve the stability of the model. The cone-tail resembles a lava lamp which is where this model acquires its name.

**Pod Racer Design**

The Pod Racer model is also based off of the Arrowhead’s body design. Similarly to the Flat-Back, the cavity at the rear of the Arrowhead is replaced with a flat rear. Additionally, two teardrop shaped pods are installed on either side of the model.
The pods will supply a generous amount of room for the generators to be housed while aiding in the transverse stability of the model. The propellers will be mounted at the rear of each pod, allowing plenty of room between them so that they do not disrupt each other.

**Hybrid Design**

The Hybrid Model was influenced by both the Arrowhead and the Concorde’s body designs, which is where it gets its name from. The model is composed of the Concorde’s overall shape, however its wings now bow outwards similar to the Arrowhead’s shape.

The Hybrid’s body design combines the best attributes of both the Concorde and the Arrowhead, thus it satisfies all of the design criteria and makes it a promising model for testing.
**Final Testing**

*Wave Tank Testing*

**Purpose**

As before, the purpose of testing in the wave tank was twofold; to test for the drag coefficients of the models as they go through the water, and to test for the overall stability of the models. For the drag test, the drag coefficient again had to be calculated using the equation for drag force. The models were again tested in the wave tank at the Florida Tech campus, using the same pulley system as before. Referring to the original Wave Tank Testing section above will provide a more detailed explanation if necessary.

**Theory**

Once again, buoyancy was a major problem for these models, and lead was once again implemented to ensure neutral buoyancy. During original testing, the location where the lead needed to be added was just estimated, basically doing a guess-and-check method. For the final testing, the center of gravity of the model was found, and the center of the lead block was placed at the center of gravity. Since it is believed that poor placement of the lead affected some of the initial results, this new method should ensure better results. All the values for how much lead was necessary can be seen in Table 3 of the data section.

Subtle changes were made to improve the results. As noted before, the fabrication of the final designs was altered, most notably was the use of the shelling tool instead of a hand saw to cut out the models. This tool created a much smoother bottom to the two halves of the model, and they fit together much better. Because of this, a shadow test was not necessary for this round of testing. Instead, getting the frontal projection area and the total area from Pro-Engineer was
sufficient. Also, since the shelling tool was so much more effective than the hand saw - belt sander combination used during preliminary testing, the gap between the model-halves was negligible, and there was no need to leave a corner of the model unsealed.

During the original testing, each of the models was harnessed using fishing line. The guide line that went through the pulley system was attached to these lines, and the model was pulled through the water. What was not noted before was just how long it took to successfully harness the models, for the fishing line was difficult to tie, and had to be glued to the models to stay in place. For the final testing, small eye screws were used instead of a harness. Attaching a key-chain ring to an eye screw was a much faster process, while seemingly causing no complications with the results.

The original trials were all run at 500g, 750g and 1000g trials. However, for the final testing, 500g was not always strong enough to pull some of the models across the tank. So the weights had to be increased. Refer to Appendix B for a detailed table showing which models required more weight to generate good trials.

Finally, the original models were all resined and fiberglassed together. For some reason, some of the models had bubbles form in the resin. Attempts were made to sand down the models, but some of the bubbles went all the way to the foam, and were impossible to sand. For the final testing, instead of using resin, a layer of gelcoat was applied. When sanded down, not only were the new models smoother than the old ones, but also there were no bubbles, ensuring smoothness throughout.

As for the stability testing, it will be carried out exactly the same as described in the original Wave Tank Testing section. The six types of motion described in this section will again be taken into account when observing the stability of the models. Since the lead was added more
accurately this time around, the models improved stability-wise.

Apparatus

The apparatus for the wave tank test was the same as that in the preliminary testing.

Procedure - Wave Tank Test (very similar to original wave tank testing)

1. Once the pulley system had been constructed and the necessary weight had been added to each model, the first step of the drag test was to attach a small eye screw to the front of each model. Some models required glue to be added around the eye screw to ensure it stayed in place. The first model tested was the Hybrid. An 8ft distance was marked on the tank as the test section.

2. The eye screw on the Concorde was attached to the line in the pulley system via a key-chain ring, to allow for easy attachment and removal once the testing of the model is done.

3. A weight of 500g was attached to a line at the end of the pulley.** The weight was lifted 11 feet off the ground, and then dropped, pulling the model across the tank.

4. There needed to be five good trials performed at this weight. A good trial was indicated when the model did not hit the sides or bottom of the tank, or break the surface of the water. The timing of the trial must also be accurate for the trail to be deemed a good one (two timers with results within 0.1 seconds of one another).

5. Once five good trials had been recorded, the weight at the end of the pulley was changed to 750 grams.**

6. Again, five good trials needed to be recorded at this weight.
7. Finally, the weight at the end of the pulley was changed to 1000g, and five good trials had to be recorded.**

8. Steps 2-7 had to be repeated for the Flat-back, Lava Lamp, and Pod Racer to complete the drag test.

** For these trials, some of the models needed more than 500g to make it across the test section successfully. Thus, the weights being added were increased. See Appendix D for a detailed table showing how much weight was required for each of the models.

Figure 52. Further testing in the wave tank

Results

Table 3: Amount of lead necessary to make the models neutrally buoyant.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lead added (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-back</td>
<td>4910.03</td>
</tr>
<tr>
<td>Hybrid</td>
<td>1864.73</td>
</tr>
<tr>
<td>Lava Lamp</td>
<td>5637.81</td>
</tr>
<tr>
<td>Pod Racer</td>
<td>6399.28</td>
</tr>
</tbody>
</table>
Table 4: The Drag Coefficients and Standard Deviations for the different areas used during the drag test.

<table>
<thead>
<tr>
<th>Model</th>
<th>Projection Area</th>
<th>Total Area from Pro-E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drag Coefficient</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Flat-back</td>
<td>0.377</td>
<td>0.01</td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.537</td>
<td>0.024</td>
</tr>
<tr>
<td>Lava Lamp</td>
<td>0.445</td>
<td>0.020</td>
</tr>
<tr>
<td>Pod Racer</td>
<td>0.605</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Discussion - Drag Test

The purpose of the drag test was to find out which model had the smallest drag coefficient. Having a small drag coefficient would indicate that the model has very little drag on it when in the water. Any drag on the model would decrease its efficiency, so the less drag, the better. Research showed that there was some discrepancy about which reference area to use when calculating the drag coefficient from the drag force equation, so both areas were used, and the two results are displayed in Table 4 of the results section. To determine which model had the least drag on it, it comes down to what one believes the reference area should be in the drag force equation. If one uses the projected area, the Flat-back was by far the best, followed by the Lava Lamp and Hybrid. However, if one instead uses the total area, it is the other way around, with the Hybrid being far better than the Flat-back and Lava Lamp. For both areas, the Pod Racer was by far the worst of the models. Also, when one examines the values for the drag coefficients located in the relevant tables in Appendix D, the values of the drag coefficients change drastically between the two tests. However, the purpose of this test was to determine which of the models being tested had the smallest drag coefficient. Effectively, this test was just for comparison. The actual numbers do not technically matter, just how they rank against those of the other models. Thus, it is up to the observer to decide which area is the proper one to be inserted into the drag coefficient equation as the reference area of the model.
As can be clearly view in Appendix B, a total of 60 trials were recorded. However, far more than 60 trials were run. As stated before, a trial was only recorded if it was a “good” trial, which is to say that the model did not hit the sides or the bottom of the tank, or break the surface of the water. Some of the models, such as the Hybrid, were very easy to test, with almost no bad trials. Other models, such as the Flat-back, took at least four trials to get one good one. Where and how the model was released was crucial to the success of the run. So all in all, it probably took 200 to 250 trials to get 60 good ones.

Error Analysis for Drag Test

Problem: Different turbidity of the water as a result of failing to let the water settle between each test.

Solution: The ocean does not have a consistent flow. Also, the water was allowed to settle while the weights/models were changed out. This is why five trials were run for each weight, and 15 total per model.

Problem: Accurately timing the trials.

Solution: Two timers were being used for each test. Since both timers were members of the group, a certain amount of human error was involved. To counter this, a trial was only considered acceptable if the two times were no more than 0.1 seconds apart (both timing devices went to 0.01 seconds).

Problem: Taking proper measurements (dimensions of the tank, mass of the weights used during the trials).
**Solution:** Two people measured the tank to double-check the dimensions. As for the scale, proper calibration of the scale was ensured by weighing something with a known weight for comparison. Also, the same scale was used for all the measurements for the test, so even if there was a problem with the scales, it would have been a systematic error (which is to say, all the measurements in the experiment would have been altered the same amount), and thus not caused any issues with the experiment.

**Problem:** The guide controlling the pulley system wobbled quite a bit during a dry run.

**Solution:** Four clamps were binding the guide to the tank as tightly as possible, allowing virtually no movement whatsoever. These clamps were checked during testing to ensure that they remained tight.

**Discussion - Stability Test**

The purpose of the stability test was to determine which of the models was the most stable in the water. Using the various ship-motions described in the theory section, each of the models was reviewed and rated for how well they did. It was important to note how the models behaved at various weights, as some did better at higher weights, while others did worse. The Hybrid was the most stable out of all of the models tested. It remained perfectly straight from all viewing angles despite the weight for which it was being tested at. In a few cases the model showed a slight yaw movement at the end of its runs; however, this happened so rarely it was deemed negligible. The Lava Lamp was the next most stable during the wave tank testing. It had one issue that consistently interrupted a majority of its trials; the model tended to sway to the left despite the weight for which it was being tested at. However, the swaying was more than likely
due to a listing problem due to inadequate positioning of lead. It was difficult to determine the exact source of the problem due to the fact that even the tiniest imperfection can influence the model significantly. The Flat-Back had a similar swaying problem as the Lava Lamp, except it was a lot more severe. The model pulled rapidly to the left as soon as it was let loose during the wave tank testing. The curious part to this problem is that the model did not yaw to the left, it simply swayed. If the nose of the model were being pulled to the left then the rest of the body would have turned and followed, this would have been a result of improper harnessing; however, the model was not led by its nose, its orientation remained straight yet it translated to the left consistently. This issue is most likely a result of a slight insufficiency in the positioning of the lead inside the model. However, the fact that both the Flat-Back and the Lava Lamp had the same swaying complication suggests that there is a deficiency with the shape of the models, especially since their designs are so similar.

**Error Analysis for Stability Test**

**Problem:** Limits of the human eye, considering this test was strictly visual observations.

**Solution:** All trials were videotaped, so they could be viewed later to observe any issues with stability.

**Problem:** Properly identifying what type of stability issues were evident in each trial.

**Solution:** It was important to ensure proper understanding of different types of stability issues before reviewing the tape. Once these issues were properly defined, a successful review was possible.
Conclusion

Based on copious amounts of research, it seems that using the total surface area as the reference area is the most logical way to go. This choice will of course be scrutinized by some, but it seems to be the best one. Given this, the Hybrid was the clear winner of the drag test. Stability-wise, the Hybrid was also the best. Other than a slight yaw that occurred on a few trials, the Hybrid’s stability was almost perfect. The Hybrid clearly won the wave tank section of the testing, but testing for streamlines in the wind tunnel and Fluent will determine if it is to become a prototype in the future.

Wind Tunnel Testing

Purpose

As before, the purpose of testing in the wind tunnel was to determine the streamline flow over the various model designs. The reason that this testing was necessary stems from the principal idea of flow-detachment points over bodies. For this final round of wind tunnel testing, the bodies were fairly similar. Three of them had the basic Arrowhead design from the preliminary testing, each with a specific difference, and this test determined if an arrowhead with a flat back (Flat-back), an arrowhead with an extension off the back (Lava Lamp), or an arrowhead with pods built in (Pod Racer) is the most streamlined. The last model to be tested was the design based on the original Concorde design (Hybrid). This experiment will prove which design has the most streamlined body.

Theory

The final wind tunnel test was performed in exactly the same manner as that of the
preliminary wind tunnel test. The only major difference was in the design of the models. Thanks to the updated fabrication of the models being so much more effective, there was no large gap between the halves of the model, and thus no need to leave a large hole in the models to allow water to flow in during the drag test. According to the wind tunnel administrator, this change would improve the overall effectiveness of the models. This would prove to be an accurate statement upon testing.

Apparatus and Procedure are exactly the same as in original Wind Tunnel Testing.

Results

Discussion

The purpose of the wind tunnel test was to determine how well streamlined each of the models was. In the preliminary wind tunnel test, the Arrowhead design was the best. The only major fault in the design (other than the hole) was the notch in the back of the model. The notch had been originally implemented to follow the standard arrowhead design, but actually proved to be problematic during preliminary testing. This time, the design was altered three ways. The first
alteration was simply filling in the notch, which was the Flat-back. After testing all the models and examining the tapes, the Flat-back appeared to be the best. There were no obvious detachment points anywhere on the model, and the streamlines across the entirety of the model seemed to hold perfectly. The next alteration was rather than having a notch into the model, there was instead a tail added to the model, which was the Lava Lamp. The idea was that the flow could hold onto the tail all the way to the end, then fall off all the way to the end. The basic concept was effective, but there was a turbulent zone at the base of the tail on both sides where it curved and connected with the back of the model. For this reason, this model was second best in the trials. The final alteration made to the Arrowhead was two-fold. Firstly, like before, the notch was removed and replaced by a flat back. Secondly, teardrop-shaped pods were added on both sides of the model. This was the Pod Racer. The purpose of creating this model was to simulate having a generator housing. Unfortunately, the pods ended up causing major problems for this design. Unlike the tail on the Lava Lamp, which maintained steady streamlines as the flow went over it, the pods on the Pod Racer caused the flow to separate as it went over the pods. This would cause a serious impedance to the flow as it made its way to the propellers, which would be stationed right behind the pods. Thus, the Pod Racer was deemed the worst of the models tested in the wind tunnel.

The only model tested in the wind tunnel during final testing that was not based on the Arrowhead was the Hybrid, which was based on the Concorde. For the most part, the Hybrid was perfect, holding its streamlines straight and flat. However, like the original Concorde design, there was a small turbulent zone on the Hybrid, located near the middle of the model on both sides, just below where the wings began. Since there was again no way of pinpointing the exact cause of this turbulence, this model was ranked third for this test. It seems likely that if the
change in height between the wings and the shaft down the middle of the model was reduced (or at least, the slope between the two was reduced), it may help to remove the turbulent zone.

**Error Analysis for Wind Tunnel Test**

**Problem:** Wall effects from the sides of the tank causing interference with the streamlines.

**Solution:** According to the wind tunnel operator, as long as at least two inches of space was left on each side of the model, the wall effects should not be a problem. None of the models tested had less than three inches of space on each side of the model.

**Problem:** Wind effects causing models to wobble as the wind currents move over them.

**Solution:** On their own, the models are heavy enough to stay in one spot. However, some of the models do not have a flat base, and thus cannot remain stable in the wind tunnel. To fix this problem, small pieces of lead left over from the drag test were placed into the wind tunnel and wedged beneath the models to hold them in place.

**Problem:** Overlapping threads causing inaccurate results.

**Solution:** When taping the threads onto the model, great care was taken into avoiding overlap. The threads were stretched to their limit, and the next thread was attached just beyond the reach of the previous thread.

**Conclusion**

The wind tunnel test was meant to reveal which of the models had the best streamlines, using the thread test. Unlike the preliminary testing, the final testing made it very difficult to
determine a clear winner. Ultimately, the Flat-back was deemed the best, but the results were much closer this time. This was the physical test for the streamlines, and Fluent will hopefully generate a computer simulation that produces similar results.

**Fluent Testing**

**Theory**

The theory for Fluent will be the same as during original testing.

**Results**

![Fluent Hybrid result](image)

Figure 54. Fluent Hybrid result

![Fluent Lava Lamp result](image)

Figure 55. Fluent Lava Lamp result
Discussion

As stated before, these Fluent trials were performed exactly as the original ones. Again, the goal was to determine which of the models produced the maximum velocity off the back of the models. All the models were subjected to a starting velocity of 2m/s. For these trials, the Hybrid was the clear winner, with an incredible velocity of 1.70m/s, a velocity better than any of these models, as well as any of the original models. The rest of the models were really not even close. The next closest model was the Lava Lamp, which produced a maximum velocity of
1.39 m/s. The Flat-back came in third, with a velocity of 1.30 m/s. Rounding out the trials was the Pod Racer, which only managed a velocity of 1.11 m/s.

**Conclusion**

The Hybrid was the clear winner of this test. The Hybrid has basically dominated all testing thus far. With a maximum velocity of 1.70 m/s, it outperformed all other models tested, proving it was the most streamlined model tested.
Conclusion

In conclusion, all eight models were subjected to the same three tests in order to determine the most efficient design. The three tests were the wave tank test, the wind tunnel test, and the Fluent test. The wave tank test was performed in order to find the drag coefficients as well as the stability of each model. The wind tunnel test was implemented to show the physical streamlines over each design shape while the Fluent test showed the theoretical computer generated streamlines over each model. A final analysis was performed for all of the test data in order to compare each of the eight models to one another. This final analysis concluded that the Hybrid is unanimously the most efficient body design. The Hybrid won three out of the four categories for which all eight of the models were compared. Also, three out of the four improved models were the top three body designs out of all eight of the models. The Hybrid, Lava Lamp, and the Flat-Back were the three most efficient models; this proves that the alterations and improvements used to create the new set of models were successful in making more adequate body designs. Overall, the dual-spiral turbine is a fun and interesting project and there is a lot of potential for it to be continued and successful in the future.
Recommendations

There are a few recommendations that should be considered by future ocean engineering teams looking to work on this project. Firstly, it is highly recommended that this project, the dual-spiral turbine, be continued and progressed in the future. Secondly, flow dividers, fins, and vertical stabilizers should be looked into; they should be designed, fabricated, attached to the Hybrid model and then tested using a similar type of drag test. Also, various types of propellers need to be researched, fabricated, and tested in order to discover which is the most efficient for a dual-spiral turbine, specifically the Hybrid body. Additionally, once the Hybrid body has been finalized and the most efficient propeller type has been discovered, a full-scale prototype of the turbine should be fabricated. It is important that the scaling is done correctly so that the dimensions remain consistent with the models. In order for a full-scale prototype to be successful there are quite a few concerns which must be considered, such as: anchoring, mooring, big swell awareness, leaking, and buoyancy.
Appendices

Appendix A – Budget and Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Size</th>
<th>Quantity</th>
<th>Supplier</th>
<th>Unit Price ($)</th>
<th>Total Price ($)</th>
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<td>Home Depot</td>
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<td>Home Depot</td>
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<td>4.93</td>
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<td>PVC Coupling</td>
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**DONATIONS**  
647.60
### Appendix B – Tables (Drag Test Data)

#### Table 5: The drag test for the Arrowhead using the frontal area found via the shadow test.

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Density (kg/m³)</th>
<th>Area (m²)</th>
<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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</thead>
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<tr>
<td>4.90</td>
<td>973</td>
<td>0.031</td>
<td>2.69</td>
<td>0.906</td>
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**Average** 0.404
**Standard Deviation** 0.012

#### Table 6: The drag test for the Concorde using the frontal area found via the shadow test.

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Density (kg/m³)</th>
<th>Area (m²)</th>
<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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### Table 7: The drag test for the Shield using the frontal area found via the shadow test.

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<th>Force (N)</th>
<th>Density (kg/m³)</th>
<th>Area (m²)</th>
<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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</thead>
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**Average**

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<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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### Table 8: The drag test for the Teardrop using the frontal area found via the shadow test.

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<th>Density (kg/m³)</th>
<th>Area (m²)</th>
<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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Table 9: The drag test for the Arrowhead using the total surface area found via Pro-Engineer.

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<th>Density (kg/m³)</th>
<th>Area (m²)</th>
<th>Timed Trials (s)</th>
<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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<tbody>
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Table 10: The drag test for the Concorde using the total surface area found via Pro-Engineer.

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<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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<tbody>
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<td>Timed Trials (s)</td>
<td>Velocity (m/s)</td>
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Average 0.102
Standard Deviation 0.003

Table 11: The drag test for the Shield using the total surface area found via Pro-Engineer.

<table>
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<th>Density (kg/m$^3$)</th>
<th>Area (m$^2$)</th>
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<th>Velocity (m/s)</th>
<th>Drag Coefficient</th>
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Average 0.056
Standard Deviation 0.002

Table 12: The drag test for the Teardrop using the total surface area found via Pro-Engineer.
| 9.80 | 973 | 0.274 | 2.03 | 1.201 | 0.051 |
| 9.80 | 973 | 0.274 | 2.04 | 1.195 | 0.052 |
| 9.80 | 973 | 0.274 | 2.06 | 1.184 | 0.053 |

Appendix C – References


