UWASHINGTON HYPERLOOP

Preliminary Design Briefing

Initial design package created by the University of Washington Seattle’s student team for the 2015 - 2016 SpaceX Pod Competition.
Finalized November 2015.

Preliminary Design Briefing Overview

Table of Contents: **Page**

- Mission Statement + Goal → 3
- About UWashington Hyperloop → 4
- Team Directors & Faculty Advisors → 5
- Team Members → 6
- Timeline → 7
- Pod Dimensions & Specifications → 8
- Profile & Statistical Aerodynamics → 9
- Pod Safety Information & Hazards → 10
- Pod Propulsion Mechanisms → 11-12
- Pod Levitation Methods → 13
- Pod Braking Methods → 14
- Telemetry & Data Streaming → 15
- Power Consumption & Stored Energy → 16
- Renders & Images → 17-20
- Sponsors → 21

GENERAL

Mission Statement + Goal

Learn. Innovate. Build . Test. Sustain. Evolve.

The goal of the UWashington Hyperloop Team is to accelerate the advent of sustainable transport by raising awareness of futuristic, zero emissions mass transportation systems. Big leaps in technology are needed and naturally invite a high level of scrutiny. New technology must be held to a higher standard of safety than what has come before.We plan to exceed the expectations and the competition.

Our team is uniquely positioned to leverage the knowledge and resources of the academic community at the University of Washington and our local aerospace industry.

GENERAL

About UWashington Hyperloop

Evolution, not iteration.

Highlights:

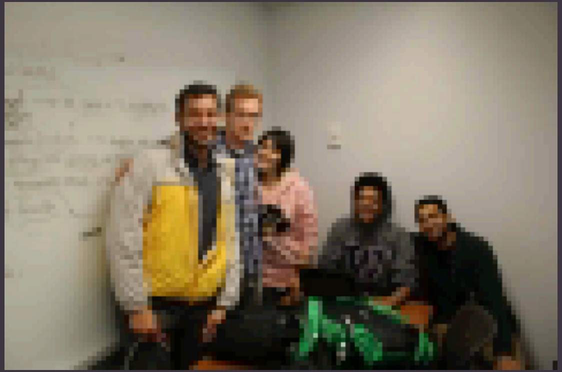
- University of Washington campus
  - Reuters rated as World's #1 most innovative public university and #4 overall
  - On campus CoMotion Labs Makerspace and Kirsten Wind tunnel supports prototyping
  - Strong connections to local aerospace industry
  - Leader in sustainability in the northwest

- Necessity for sustainable transport
  - Transportation industry responsible for 21.4% of rejected energy (LLNL.gov)
  - Only a technological leap can accelerate the slow 5% annual improvement of average EPA fuel economy

- Breadth of team members/advisors
  - Multidisciplinary : Engineering, Physics, Math, Design, Psychology , Business
  - Diverse cultural background : 39 Students

- Intention to design **AND** build a pod
  - We plan to design, test, and manufacture a fully functioning pod to compete with in the June.

- Plan beyond the competition
  - Develop annual cycle to represent engineering team, similar to SAE held competitions
  - Develop a proposal for the Pacific Northwest implementation of the Hyperloop



GENERAL

Team Directors & Faculty Advisors

Michael Chamerski
Founder / Director
Power Distribution & Storage // Public Relations Team Lead
Major: Applied Physics

Malachi Williams
Director
Propulsion // Manufacturing Team Lead
Major: Civil / Mechanical Engineering

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Robert (Bob) Breidenthal
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Professor Breidenthal obtained his doctorate degree in Aeronautics at the California Institute of Technology in 1979. He has received support from the Air Force Office of Scientific Research, the National Science Foundation, NASA and Asea Brown Boveri, Ltd. of Switzerland. He has done consulting work for The Boeing Company, Rocketdyne, ARCO Alaska, U.S. Gypsum, Peerless Manufacturing, Asea Brown Boveri, Learjet, Vornado, Mallen Research and Centriflo.

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Team Members

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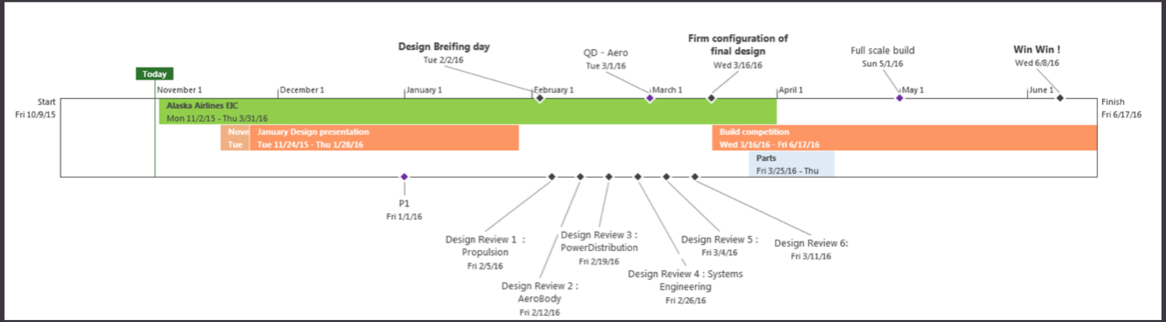
Colin Summers	*Power Dist.*	Morenike Magbagbeola	*Systems Eng.*		

Timeline

Our efforts are coordinated for a successful POD build and ready to race at the competition weekend June 2016
We have scheduled buffer for the potential of an early summer race
Concurrently, we are building relationships with sponsors to facilitate parts sourcing before the Design Weekend



- **Design Milestones**
  - Feb : Sub-team reviews
  - Mid March : Firm Config
- **Prototyping & Build Milestones**
  - January : P1 small scale
  - Early March : ¼ scale for Wind Tunnel
- **Full Scale Build to Race**
  - March - Mid April : Part sourcing
  - Early May : Full scale Build complete
  - Early June : Transport Pod to California race track
- **Alaska Airlines Environmental Innovation Challenge**
  - Fundraising to support prototyping
  - Recruiting and Sponsorship Outreach

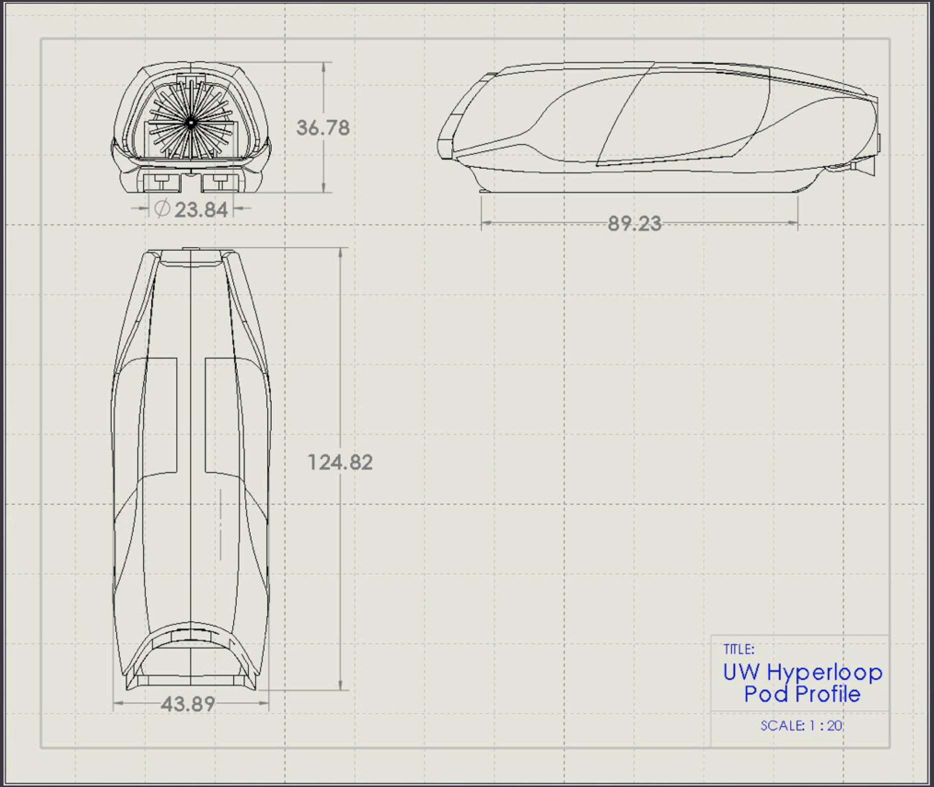
AERODYNAMICS
Pod Dimensions & Specifications

Estimated pod mass, dimensions, and other physical specifications.

Estimated Pod mass:
- Structure: Aluminum frame = *350 lb (158 kg)*
- Carbon fiber body = *140 lb (63 kg)*
- Axial Electric Fan = *440 lb (200 kg)*
- Magnetic levitation systems = *220 lb (100 kg)*
- Batteries = *500 lb (227 kg)*
- Pressurized air tank = *110 lb (50 kg)*
- Total Pod mass = *1760 lb (800 kg)*

Estimated Pod dimensions:
- Total length = *125 in (3175 mm)*
- Maximum height = *37 in (940 mm)*
- Maximum width = *44 in (1118 mm)*

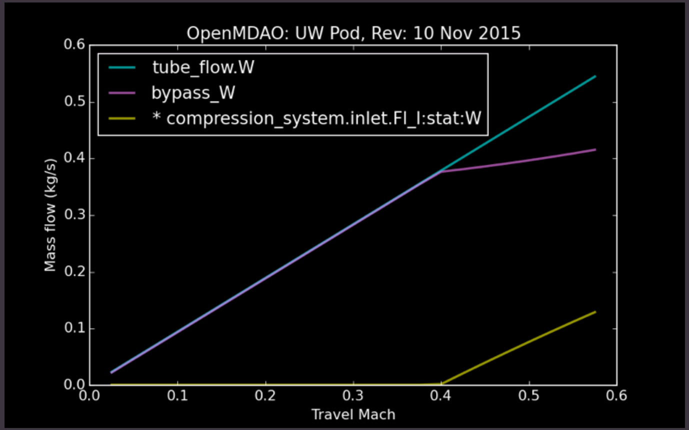
Pod structure and materials:
- A hybrid semi-monocoque/space frame type structure
- Aluminum structural tubing will form a base frame which will hold all primary components (axial fan, magnetic levitation systems, batteries, air pressure tank)
- Aluminum frames and stringers will support the outer body made of Carbon Fiber Reinforced Polymer
- A Glass Fiber Reinforced Polymer (GFRP) sheet will form the floor for the pod interior
- Alternatives: High Strength Steel components will be incorporated in the aluminum structure as needed. GFRP might be used instead of CFRP for outer body depending on cost/ weight/strength.



All dimensions shown above are in inches

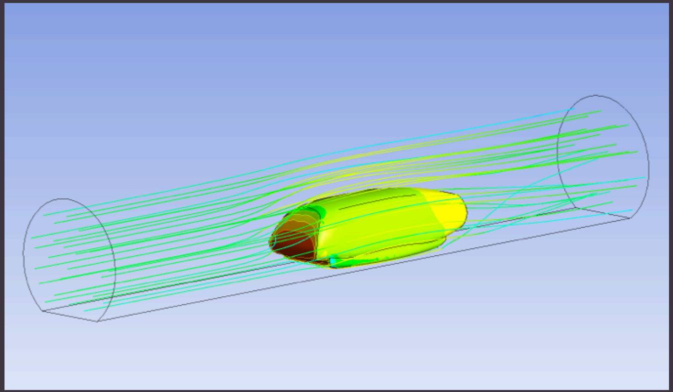
AERODYNAMICS
Profile & Statistical Aerodynamics

Details on pod shape + statistics and analysis for current profile.



Mass flow estimates
‡choked Mach of 0.9 is assumed, allowing for a margin of error

Inlet Area	733.9 in^2	0.4737 m^2
Maximum Cross-Sectional Area	1323.33 in^2	0.8538 m^2
Approximate‡ Kantrowitz Limit	Mach 0.4	306.9 mph



Though a fan is not needed to overcome the Kantrowitz limit at test speeds up to at least 300 mph, a fan and/or a diffuser at the inlet will be used to reduce pressure at the front of the pod (see red region on model) and improve scalability for different tube sizes and travel speeds.

Pod Safety Information & Hazards

Safety information, stored energy features and hazardous materials within pod.

Pressured Vessels:
- The onboard pressure vessel will be a tank that is used for scuba diving
- It will hold 100 - 200 cubic feet of air at around 3000 psi
  - Aftermarket tanks:

Stored Energy:
- The sole source of stored energy within the pod will reside within the battery array, providing large amounts of continuous current and a stable voltage, at maximum power of up to 84 kW.

Hazardous Material Information:
- Lithium-ion batteries contain a flammable electrolyte and are kept under consistent pressure, hence, creating a possible safety risk. $LiFePO_4$ batteries are, however, more resilient to chemical reduction reactions due to strong molecular bonding. Manganese-based arrays maintain extensive thermal stability and reliability, preventing thermal runaway.

Safety features and mechanisms.

Structural Integrity:
- A certification checklist based on regulatory agency requirements (Title 14 CFR or or other appropriate regulations) as applicable to the Hyperloop Pod will be satisfied to ensure integrity of pod structure. Test or analysis supported by test will be used to satisfy the checklist
- The primary pod structure will be designed to hold all major pod components in place in case of a crash caused by failure of pod levitation and/or propulsion systems.

Standard Safety Features:
- A standard set of airbags that appear on planes and trains.
- The standard seatbelt design used in Tesla cars.
- Standard oxygen masks present in planes.

Automated Safety Mechanism:
- Real-time attitude sensors and processing systems will ensure that, in the case of an emergency, there is automatic control of pod positioning.
- Other real-time sensors will measure specific boundaries such as pressure or system temperature and send alerts to associated systems. These alerts will progress in a tiered fashion from “normal levels” to “warning levels” to “emergency levels” with each tier corresponding to an appropriate response from the associated system. This will allow us to automatically prevent onboard emergencies from occurring.

Pod Propulsion Mechanisms

Detailed descriptions of the pod propulsion systems.

Overview:

Given that we will be using the concrete pusher to bypass the acceleration phase of the pod test flight, our plan is to mount an axial electric fan at the front of the pod to rapidly transfer air from the front of the pod to the rear nozzle to prevent choking flow (and to a lesser extent serve as a propulsion mechanism).

We decided on an axial electric fan over an axial compressor fan due to the onboard pre-pressurized air tank that will serve as a low speed propulsion mechanism and help maintain speed during the coast phase of our test flight. Because of this, the efficiency requirement of the axial fan can be greatly reduced with the added benefit of increased weight savings (no cooling systems for compressed air) and power consumption savings (less electrical systems). Although the caveat to this is that we are facing a problem searching for axial electric fans that:

1. Efficiently operate in a low pressure environment
2. Given our pod dimensions, can handle a high CFM volumetric flow rate of air

Therefore, it is in our best interest to design a diffuser nozzle to decrease the flow rate of air at the face of the axial fan so that we can take advantage of a larger breadth of the axial electric fan market. The table on the right provides a short list of axial fans we are investigating for use inside of our pod.

Possible Axial Electric Fan Suppliers List (as of Nov 12 2015)	**Model**	**Mass**	**Power Usage**	**CFM**
Cincinnati Fans	TAF	150 kg *(estimate)*	8.6 kW	44490
Sodeca	HTP-71-2T-20	198 kg	15 kW	23102
Sodeca	HTP-90-4T-20	266 kg	15 kW	29458

Pod Propulsion Mechanisms (Continued)

Continued detailed descriptions of the pod propulsion systems.

Axial Electric Fan Design Parameters:

The figure to the right highlights the general equations that we at first were using to estimate volumetric flow rate (CFM) and power requirements (kW) for a suitable axial electric fan for our pod.

Now, implementing the OpenMDAO plugin and pyCycle thermodynamic analysis tool has allowed us to further verify our mass flow at the front face of our fan and power requirement values.

Using the equations below we can solve for our axial fan design parameters.

P_1 = 100 Pa
P_2 = 150 Pa (Assuming Pressure ratio of 1.5)
T_1 = 292 K
V = 120 m/s
A_{inlet} = 0.33 m^2

γ = 1.4 (Heat specific ratio of air)
T_2 = Air Temperature after fan
$\dot{m}$ = Mass Flow entering fan
C_p = 1.005 kJ/(kg*K) Constant Pressure Specific Heat
$\dot{Q}$ = Volumetric Flow Rate
$\dot{W}$ = Power (kW)

$$\frac{P_2}{P_1} = \frac{T_2^{\frac{1-\gamma}{\gamma}}}{T_1^{\frac{1-\gamma}{\gamma}}}$$

$$\dot{W} = \dot{m} * C_p(T_2 - T_1)$$

$$\dot{m} = \rho * V * A_{inlet}$$

$$\dot{Q} = V * A_{inlet}$$

Note for $\dot{W}$ we will also need to take into account the efficiency of the fan, we are assuming isentropic flow as a perfect fan does not exist. We are currently estimating 15% higher power output than the ideal fan power output.

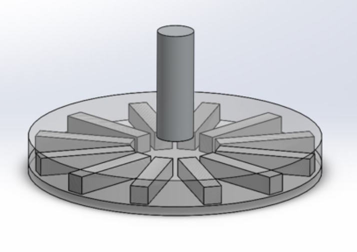
Pod Levitation Methods

Detailed descriptions of viable pod levitation methods.

Option 1: High RPM Neodymium Magnets:

This concept would work by applying angular velocity to a circular magnetic Halbach array. This causes the magnets in the array to move with a velocity relative to the aluminum track which causes eddy currents to flow in the aluminum. These eddy currents in turn produce an opposing magnetic field which generates lift on the array. The array would be produced so that the diameter of the array would be similar to the width of the track for the most efficiency in creating lift.

The following suppliers for Neodymium Magnets have been identified: KJ Magnetics, Grainger, Magnetic Hold Company, Magnet Source, United Nuclear, CMS Magnetics and Applied Magnets. 2x1/2x1/2" Neodymium Magnets cost about 4 dollars each and each array would use about 20 magnets. Adding in additional materials, each array could cost under 200 dollars, not including the motor necessary to drive the array.



Option 2: Rare Earth Metal Magnets/Stationary Halbach Array:

In order to levitate the pod with a fixed Halbach array, current would have to be applied to the aluminum track for low speed levitation, since at low speeds there is little relative motion between the array and the track. With little relative motion, there will not be enough current induced in the track to give enough opposing magnetic field and force to lift the pod. Thus the current will be needed at low speeds to boost the opposing magnetic field.

The components attached to the pod would simply be an array of magnets, so this is potentially a cheap option. However, energy would need to be applied to the track increasing the cost and complexity.

Option 3: Arx Pax:

The Arx Pax motors work in a similar fashion to the previously described rotating Arrays.

According to the Arx Pax specification sheet, the motors require 70W per kg lifted, with a pod mass of 700 kg (excluding the levitation system itself) this translates to 49kW required to lift the pod. If each motor is to lift 40kg, 18 motors will be needed and a levitation height of 7mm will result.

This is the most costly option as each motor costs $4850

SUSPENSION

Pod Braking Methods

Detailed descriptions of viable pod braking methods.

1. Eddy Current Braking:

The primary braking system of our pod. We will use a halbach array of neodymium permanent magnets that will be located near the Aluminum I-beam of the track. When the pod is moving and the magnets are close enough to the beam eddy currents will be induced in the I-beam creating a magnetic field that opposes the motion of the pod. To brake at a rate around 0.5 g's we will need to create 3900N of force based on the pod's weight. To achieve this an array of magnets will be located on either side of the I-beam. The arrays will have a dimension of 2m x 31mm x 50mm. Engaging and disengaging the brakes will be done by varying the size of the air gap between the magnets and the beam. Magnet pricing is discussed in the levitation methods section.

2. Fixed/Deployable Wheels:

This will be a supplementary braking system to the eddy current brakes. We will have mechanically deployed (or fixed) wheels to provide a low speed propulsion and braking system. The wheels will use disk brakes to stop.

3. Friction Brake:

Another possible supplementary braking system to the eddy current brakes. A brake caliper that attaches around the I beam and contacts the main body of the beam. This may also be a low speed and an emergency braking system.

4. Aerobraking / Choke Flow:

As an alternative to the eddy current brakes for the primary braking system simple drag induced aerodynamics would slow the pod down. Aero panels would fold out to increase surface area of the pod thereby increasing drag to slow down. furthermore for emergency braking purposes the fan would be stalled to provide a choke further increasing braking force.

SYSTEMS ENGINEERING

Telemetry & Data Streaming

Component Listing: (as of Nov 12 2015)	Model:	Sensor Type:	Power Usage:	Quantity:
Position/velocity in tube:	**TCRT5000**	**Optical sensor**	**5 V / 1 mA**	**1**
Acceleration in tube and Vehicle attitude (roll, pitch, yaw):	**LSM9DS0**	**Accelerometer Gyroscope Compass Magnetometer**	**3.6 V / 350 µA**	**1**
Pod pressure/ temperature:	**BMP180**	**Barometric Pressure Altitude Temperature**	**3.6 V / 5 µA**	**2**
Power Consumption:	**INA219**	**High side DC Current Sensor**	**3.6 V / 350 µA**	**3**
Flow of Axial Electric Fan	**FS5**	**Thermal Mass Flow Sensor**	**5 V / 200 mA**	**1**

The following pod telemetry will be measured using sensors described below. Arduino MCU will be used to retrieve telemetry data and CAN buses will create a central networking system to allow communication between different systems of the pod.

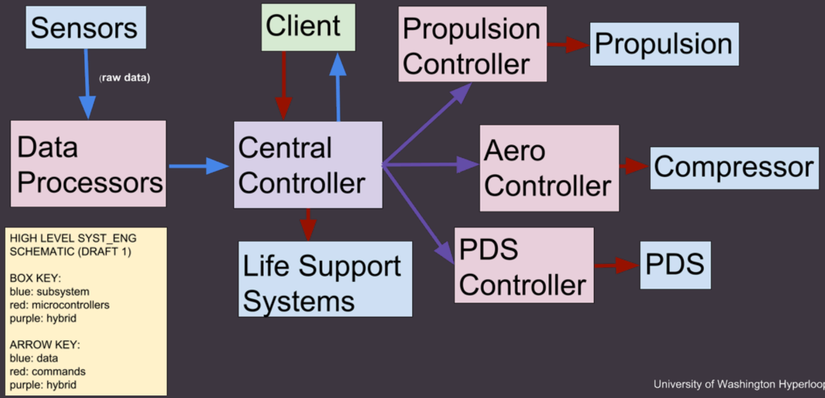
Position/Velocity in tube:
The position and velocity of the pod are measured using an optical sensor that uses the reflective marks inside the tube.

Acceleration in tube and Vehicle attitude (roll, pitch, yaw):
To more accurately measure the acceleration and altitude of the pod, an accelerometer, gyroscope, compass, and magnetometer will be utilized.

Pod pressure/ temperature:
The pod pressure and temperature are measured with a sensor that records barometric pressure, altitude and temperature.

Power Consumption:
The power consumption of different components of the pod will be measured with a high side DC current sensor.

Flow of Axial Electric fan:
The flow in/out of the axial fan and/or tank will be measured to calculate pressure inside a reservoir.



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POWER DISTRIBUTION & STORAGE

Power Consumption & Stored Energy

Detailed descriptions and mathematics on power consumption and storage.

Component	Power (kW)	Runtime (min.)	Energy Req. (kWh)
Axial Electric Fan	15	20	5
Magnetic Levitation	56	20	18.7
Systems Components + Other	2	20	0.7
Total	73	20	24.4

We will allow ***20% additional headroom*** for unforeseen power draw and to prevent complete discharge of battery:

$$24.4\ kWh * 120\% = 29.28\ kWh \sim 30\ kWh \quad (1)$$

Axial Electric Fan

Based on calculation from the aerodynamics and propulsion teams, the axial fan for the pod will require 15 kW for a 20 minutes runtime duration. Its total energy requirement was estimated to be 5 kWh.

Magnetic Levitation

Since the pod will be using magnetic levitation to support its weight, required power will depend on the weight of the pod. Our team will be implementing a Halbach Array, similar to the technology used by Arx Pax.

According to Arx Pax's standard datasheet, magnetic levitation consumes 70 W per kilogram of lift. If we assume pod weight to be 800 kg, magnetic levitation systems will consume around 56 kW.

Systems Components

For the systems components we estimated that the system will required around 2 kW of power and 0.67 kWh of energy.

In total, with the three components above, the estimated total power requirement results in 90 kW with total required energy of 30 kWh at a runtime of 20 min.

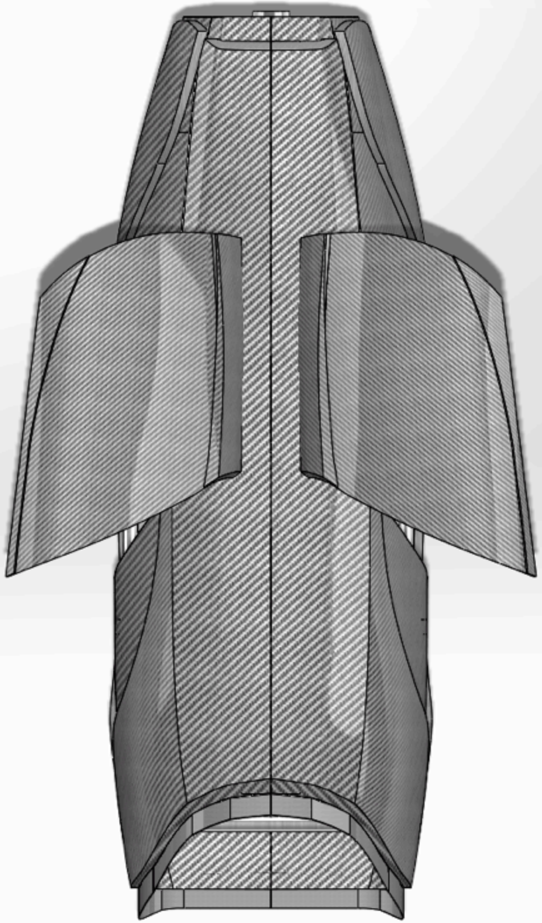
Battery System

The specifications of three prospective battery arrays are as follows:

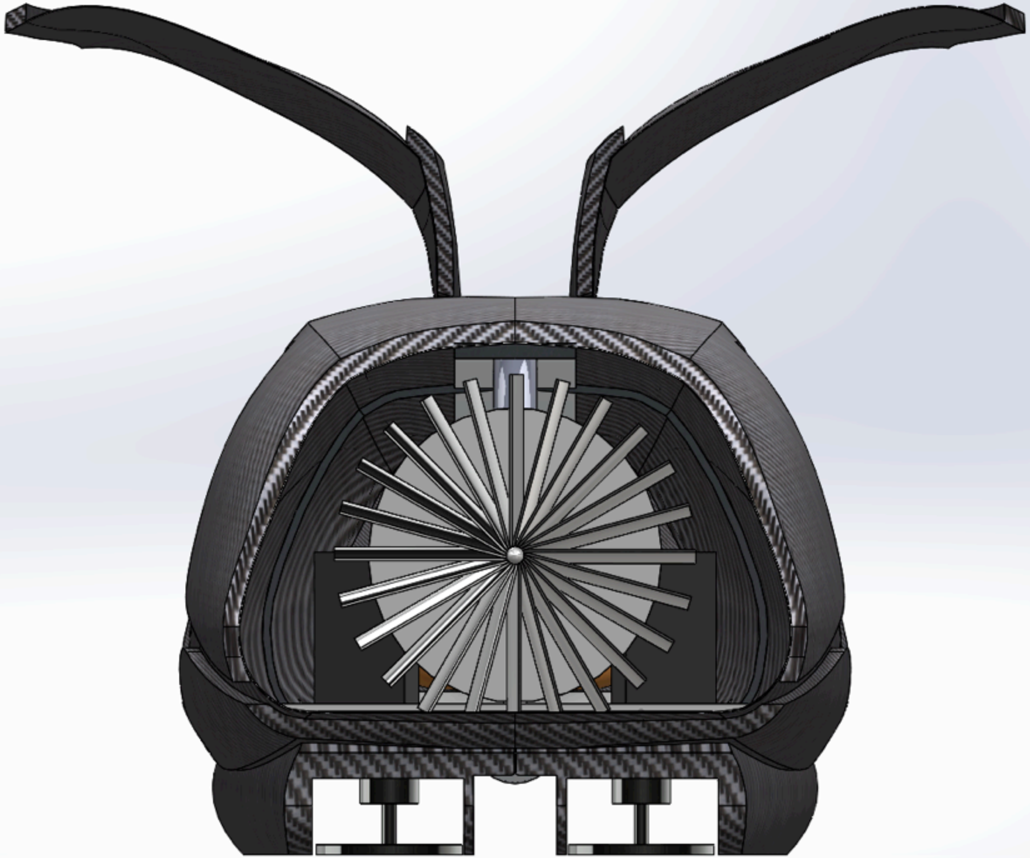
Battery Information	LG Chem Mn-Based Cell	CALB CA400	A123 Systems AMP20M1HD-A
Voltage (VDC)	96	3.2	3.3
Continuous Current Draw (A)	45	400	19.6
Maximum Current Draw (A)	205	2000	364
Battery Chemistry	$LiMn_2O_4$	$LiFePO_4$	$LiFePO_4$
Internal Resistance at 40° (Ω)	0.15	0.40	0.55
Operating Temperature (°C)	-35 - 55	-20 - 55	-30 - 55
Capacity (Wh)	4320	1280	65

Renders & Images

Top Profile



Front Profile



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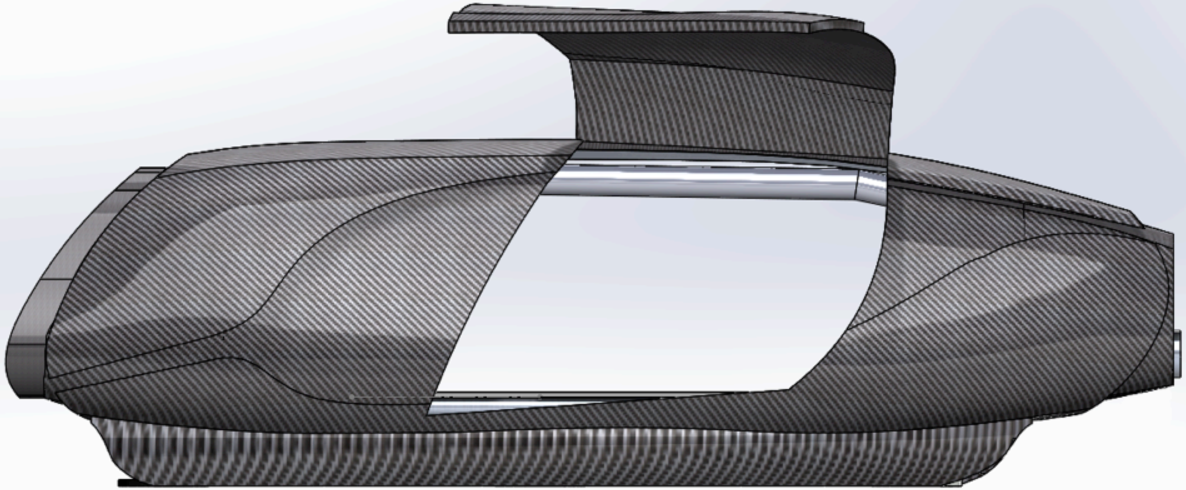
Side Profile



Special thanks to SpaceX for providing an unparalleled opportunity to propel civilization into an era of incredible potential!

~ UWashington Hyperloop