BADGERLOOP

FINAL DESIGN PACKAGE

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

MISSION OVERVIEW

We, the BadgerLoop team, students of the University of Wisconsin-Madison are striving to secure funding in order to build a pod and participate in the Competition Weekend.

Our fifteen-foot BadgerLoop Pod will levitate using Halbach arrays and brake using a regenerative, contactless eddy current scheme. Our lightweight yet durable outer shell houses numerous robust and innovative safety and control systems, built on a lightning fast Controller Area Network

BADGERLOOP TEAM INFORMATION

- Competition Objective
  - We will present our pod at Design Weekend
  - We will build and fabricate competition-scale pod for testing in SpaceX Test Tube during Competition Weekend
- Pod Testing Category
  - Levitating (non-wheeled) Pod
- Team Size
  - 6 Executive Members
  - 7 Team Leaders
  - 86 General Members

BADGERLOOP TEAM STRUCTURE

Executive Team

Tieler Callazo
Co-President

Brett Sjostrom
Co-President

Duncan Adams
Technical Director

Sid Smith
Industry Relations

Johnnie Wagman
Team Coordinator

James Olson
Financial Director

Team Leaders

Austin Jeffries
Mechanical

Eric Amikam
Electrical

Chase Roossin
Software

Alex Balister
Safety

Michael Knippen
Operations

Bill Carpenter
Levitation

Seth Rueter
Braking

General Members

Kevin Bannerman
Jonathan Barker
Matthew Benbenek
William Black
Jesse Bonney
Derek Burling
Andrew Bugliosi
Ryan Castle
Brandon Cole
Patrick Cummings
Kyle Curry
David Doellstedt
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Bryce Kramer
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Benjamin Moldenhauer
Kellen Moore
Jonathan Murray
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Thomas Petrovic
Carlos Pimentel
Samuel Pochyly
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Noah Pulvermacher
Daniel Quigley
Kyle Raddatz
Daniel Radtke
Noah Rhodes
Jackson Roach
Elijah Ruder
Christopher Rupel
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Justin Shrimmer
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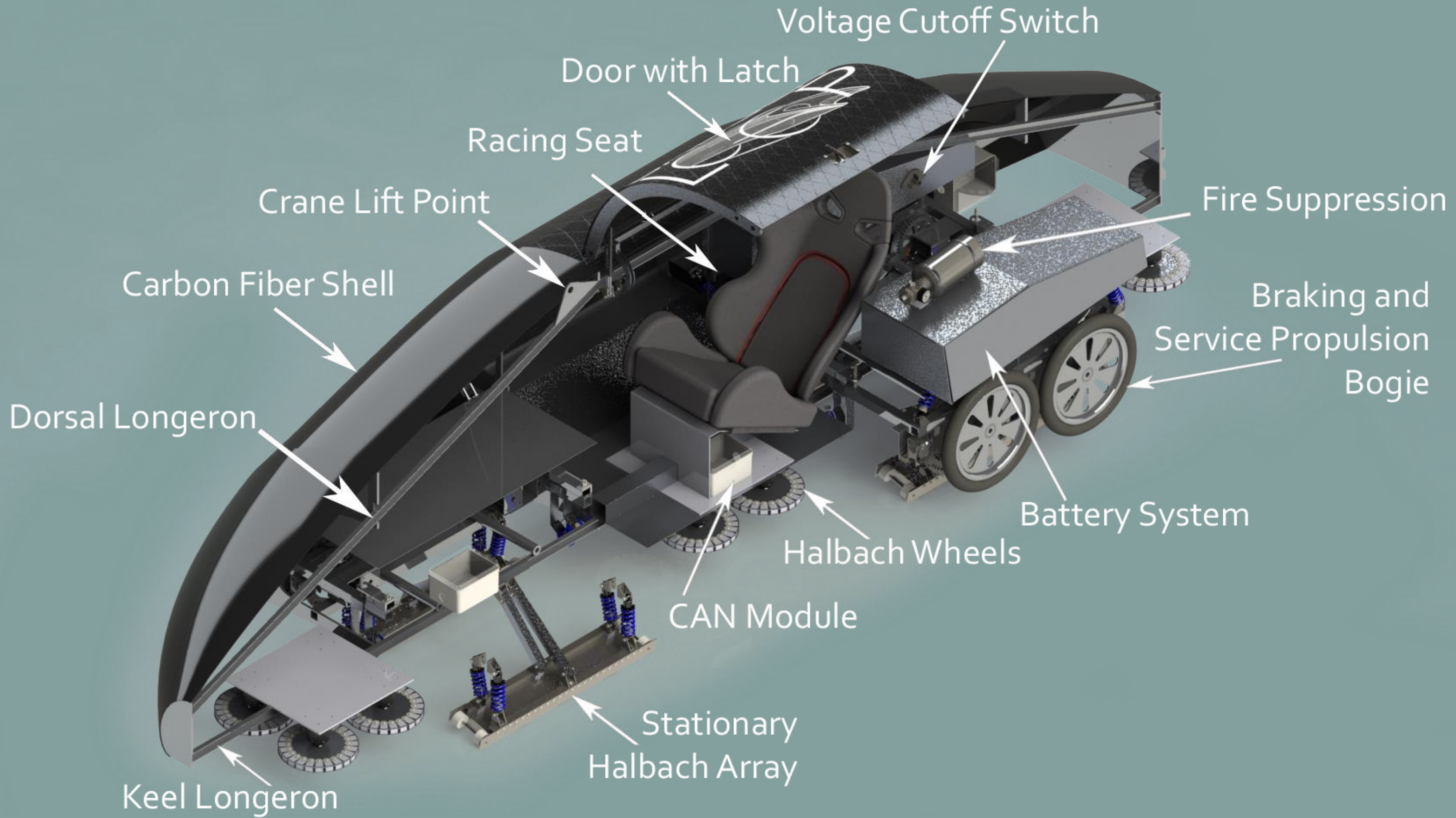
Tucker White
Justin Williams
Andrew Winans
Evan Wolfenden
Johnny Yan
Rachel Yehle
Jameson Zaballos
Troy Zeuske
Jia Zhuang

Faculty Advisors
Dr. Michael Cheadle
Dr. Christopher Rutland
Dr. Duncan Carlsmith

SYSTEM OVERVIEW



COMPETITION LOGISTICS

1) Functional tests and load pod into tube

Distance: 0 [ft]

2) Pod interfaces with pusher and accelerates to operational speed

Distance: 0 [ft]

3) Pod levitates on Halbach arrays and maintains speed and stability with rotating Halbach wheels

Distance: 800 [ft]

4) Halbach wheels slow down resulting in a small braking force while still maintaining stability function

Distance: 3500 [ft]

5) Wheels deploy and eddy braking is fully engaged

Distance: 4280 [ft]

6) Pod comes to stop in egress 50 [ft] from tube end

Distance: 5280 [ft]

This competition plan is subject to change. We have the ability to brake faster or more comfortably if need be.

COMPETITION LOGISTICS PLAN

- Pod Loading
  - Pod will be secured and unloaded directly off the trailer on its load bearing points up on to the Ingress staging area using the SpaceX provided crane and/or forklift (SpaceX, 2015)
  - The Halbach wheels will be carefully slid over the rail where the pod will rest on its roller bearings on the Ingress exterior pylon
  - Functional Test A/B/C/D will be performed before launch

- Pod Unloading
  - Once pod is in the ready to remove state on the exterior pylon following service propulsion, the pod will be completely powered down
  - Provided SpaceX crane and/or forklift in Egress will slide the pod's Halbach wheels off of the rail and lower the pod onto our trailer

FULL DESCRIPTION OF FUNCTIONAL TESTS

- Functional Test A
  - BadgerLoop pod power up sequence will be completed in the staging area using remote startup. After power up has been completed, 2 way communication between the pod's Wireless Connectivity Module and server will be demonstrated showing the Vehicle Control, Environmental Control, and Breaking and Propulsion Modules powered on and ready to launch. Sensor data including pressure, power consumption, and temperature will continuously be displayed.
- Functional Test B
  - The Halbach wheels will be spun up to demonstrate their functionality in providing stability and forward thrust to the pod.
- Functional Test C
  - Continuous communication link will be established between the pod and the server at which point the tube will be depressurized to 0.2PSI. All sensors will be sending all data to the BadgerLoop Dashboard.
- Functional Test D
  - Halbach Wheels will begin to spin slowly, providing stability along the center rail, but no forward thrust. At this point the propulsion interface will connect to the pod.

READY-TO-LAUNCH CHECKLIST/STATE DESCRIPTION

- Pod state and power on
  - The pod be powered on and all modules will be in NSYNC mode
  - Pod will check to see that enough power is available to complete the run
  - Pod door is closed
- Wheels up
  - Making sure the wheels are up and ready to deploy for braking
  - Pod will rest on the nylon bearings of the Halbach arrays
- Environmental Conditions
  - The tube is at operating pressure used for aero calculations and at an acceptable temperature
  - Gate 1 is closed
- Levitation
  - Halbach wheels are spinning at 1200 RPM to provide stabilization once levitated
- Propulsion interface connected
  - Successful connection with the propulsion vehicle
  - Force sensor receiving data

READY-TO-REMOVE CHECKLIST/STATE DESCRIPTION

- Pod stop point
  - Pod stopped within 50 feet of gate 2 near Egress
- Battery State
  - Batteries are within a safe operating temperature
  - Batteries contain enough power to successfully use service propulsion to exit the tube
- Halbach Wheels
  - Halbach wheels are turned off for service propulsion
- Wheels down
  - Wheels are still down and usable for service propulsion
- Brakes Disengaged
  - Eddy current brakes are turned off
- Environmental Conditions
  - Tube has been pressurized and gate 2 is open

COMPETITION LOGISTICS

1. Pod accelerated by the SpaceX pusher to 260 [ft/s]

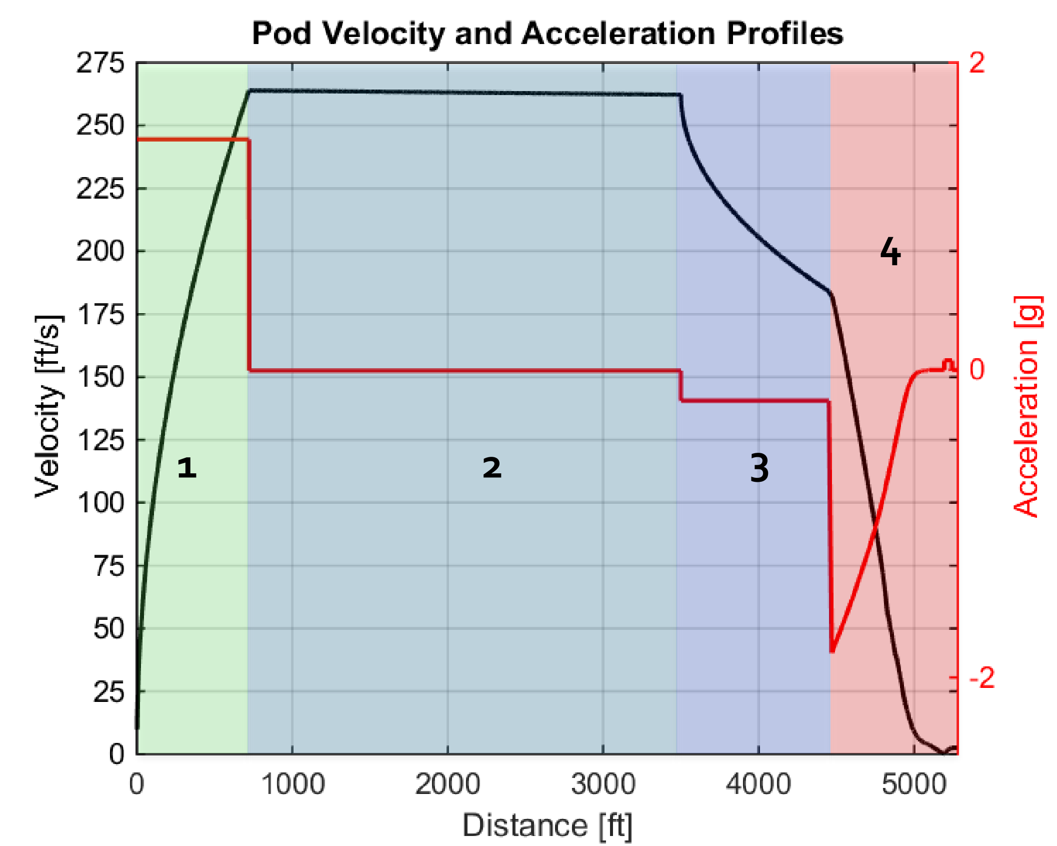
2. The Halbach wheel stability thrusters will be actively controlled to maintain the speed at 260 [ft/s]

3. The Halbach wheel thrusters will be turned down to begin slowing our pod before the wheels deploy

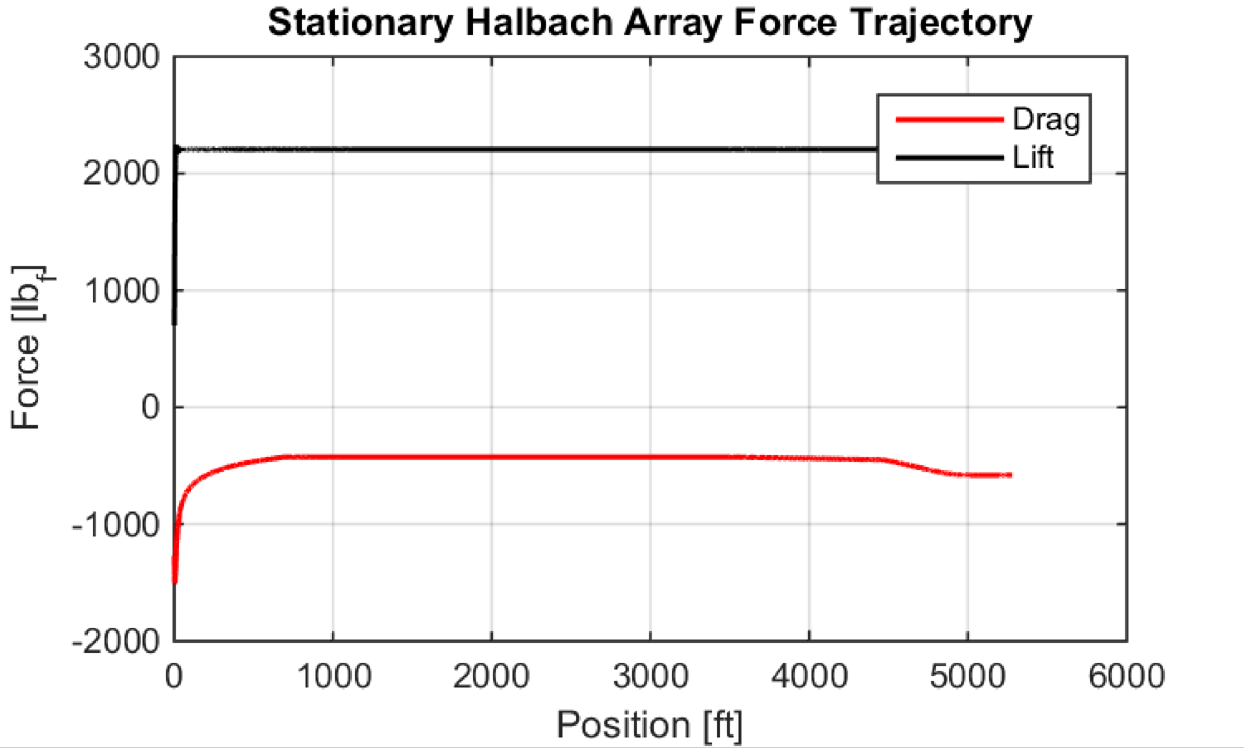
4. The wheels fully deploy and begin eddy braking
    - The eddy brakes will be modulated in order to maintain a comfortable deceleration (under 1g)
    - However shown here is the response for maximum eddy braking force

Braking during competition will begin earlier than depicted in the figure to the right

- Figure shows the worst case scenario of braking

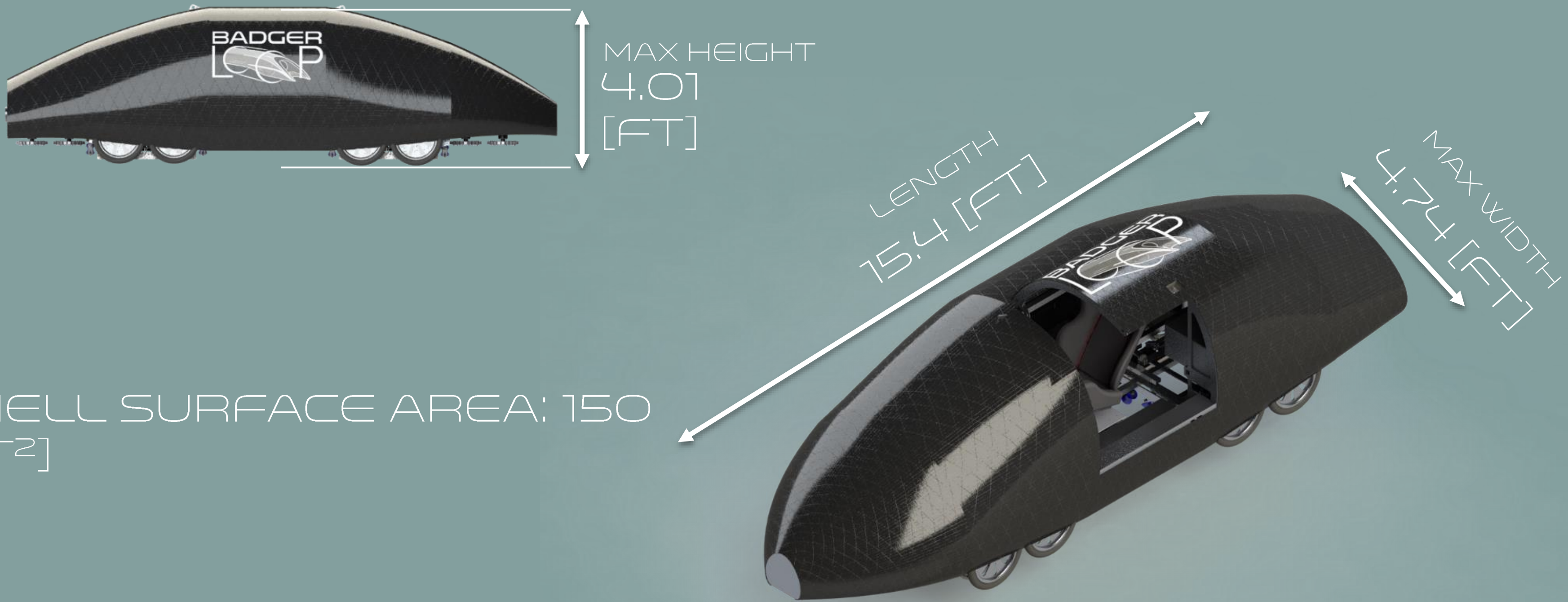


FORCE TRAJECTORY



This graph follows the velocity profile of the pod (on the previous slide) for the forces induced by passive Halbach array operation

OVERALL POD DIMENSIONS



SHELL SURFACE AREA: 150 [FT^2]

MASS, POWER CONSUMPTION & COST

Subsystem	Mass [kg]	Power [Wh]	Cost
Aluminum Frame	89.3	-	$2,850.00
Carbon Fiber Shell	59.4	-	DONATED
Braking, Suspension & Low Speed Propulsion System	210.0	320	$5,972.27
Levitation System	134.6	-	$5,795.00
Electrical System	203.1	76.7	$10,672.00
Stability & Propulsion System	71.3	240	$5,885.00
Fire Suppression System	29.8	-	DONATED
POD TOTAL	**994.5**	**636.7**	**$30,968.37***
PAYLOAD	**605.5**		
TOTAL CAPABILITY	**1600**	**10,000**	

*See Bill of Materials in the Appendix for detailed cost break down

SHELL OVERVIEW

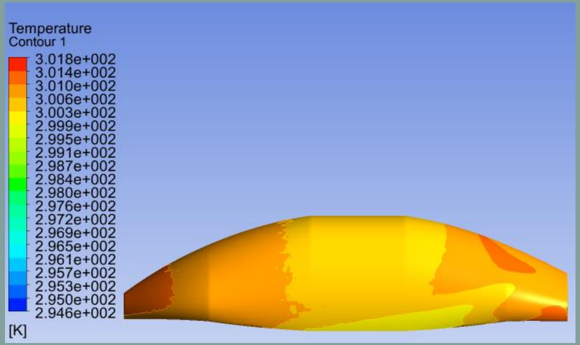
CFD Assumptions
- Ideal Gas – Air
- P = 100 Pa, T = 300 K
- k-e turbulence model
  BC's: Velocity Inlet, Pressure Outlet

Shell Properties (Carbon Fiber)
- Thermal Conductivity: 24 [W/m°C]
- Specific Heat: 795 [J/kg°C]
- Surface Roughness: 0.01

Aerodynamic Coefficients
- Drag Coefficient: Cd = 5.05
- Lift Coefficient: CL = 2.16
- Longitudinal Static Stability: (Cm)α = -0.46

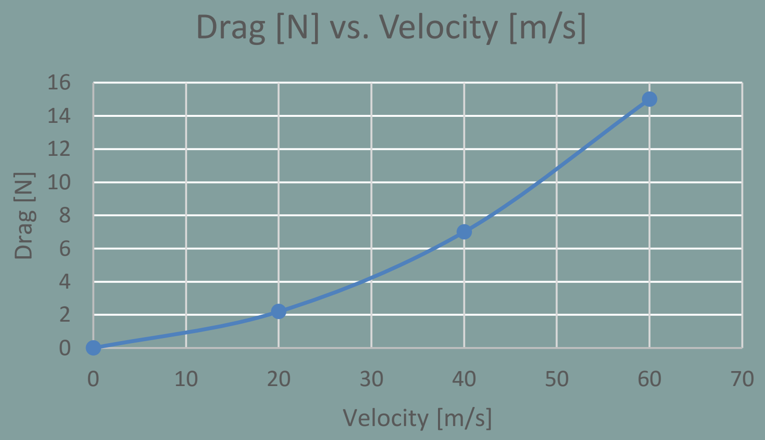
Thermal Profile (Velocity = 40 [m/s])
Minimal temperature change on carbon fiber shell

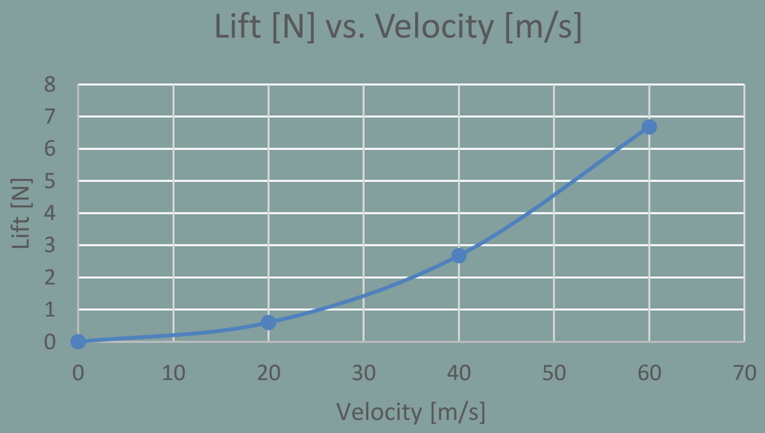
Thermal Profile



Pod Shell

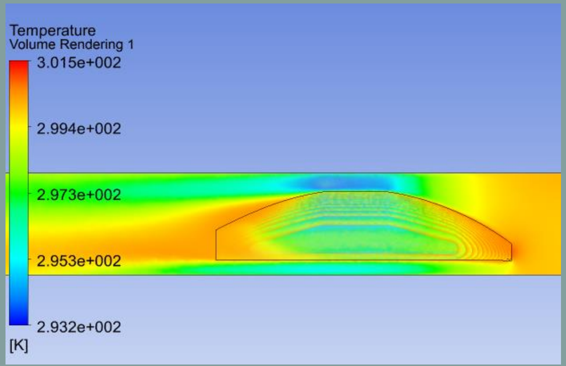
SHELL OVERVIEW





As expected, drag and lift force are approximately proportional to the square of velocity

- The drag and lift coefficients of 5.05 and 2.16, respectively, were determined by linear regression



Additional Figure: Temperature Volume Rendering (velocity = 40 [m/s])

SHELL MANUFACTURABILITY

- Uses 2000 [ft^2] of donated carbon fiber prepreg
- 6 female fiberglass molds will be used to form 7 sections (two sections are symmetric)
- Estimated manufacturing time: 11 Weeks

MOLD CREATION

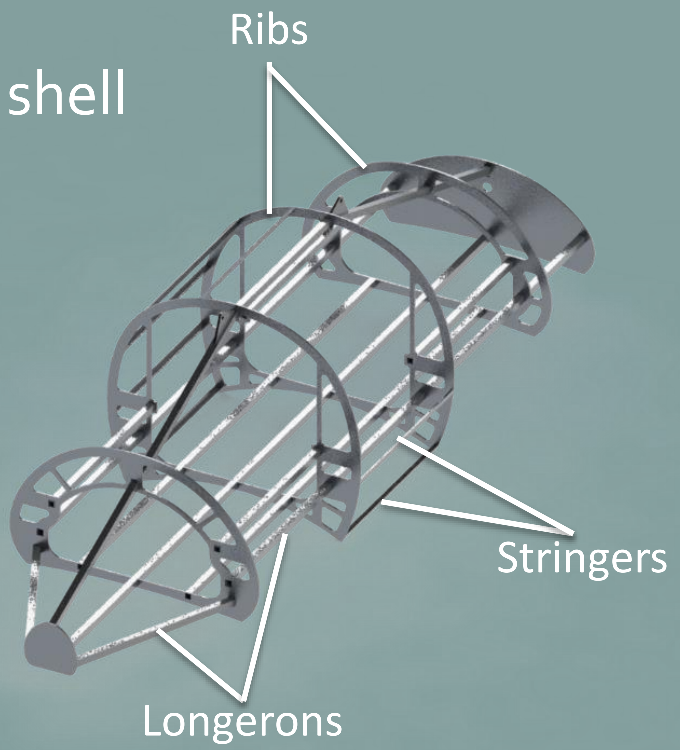
- Many profiles of insulation foam will be precisely cut, connected and sanded down to create a dimensionally accurate male plug
- Using chopped strand mat, a fiberglass female mold will be created on the male plug
  - Note: Female molds have better surface quality than male molds

SHELL MATERIALS

Shell Materials	**Mass [kg]**	**Cost [$]**
Carbon Fiber Prepreg	59.4	DONATED
Male insulation foam molds	-	$628.00
Fiberglass mold materials	-	$891.10
TOTAL:	**59.4**	**$1,519.10**

INTERNAL STRUCTURE OVERVIEW

- Semi-Monocoque design
- Flexibility to choose outer attached shell
- Primarily 6061-T6 Aluminum
  - lightweight and strong
  - can be welded (TIG)
  - inexpensive and easily attainable
  - non-magnetic material
- Easy mounting for all subsystems



INTERNAL STRUCTURE - RIBS

Functionality:

- Hold longerons and stringers in place
- Set and support curvature of outer shell

Material:

- 0.375" 6061-T6 Aluminum Sheet
  - Lightweight and high-strength

Manufacturing:

- Water jet to cut out rib shape
  - Allows for quick and precise manufacturing

INTERNAL STRUCTURE – LONGERONS

Functionality:

- Disperse external loads throughout pod
- Provide longitudinal strength

Material:

- 1.5” x 0.125” 6061-T6 Aluminum Tube

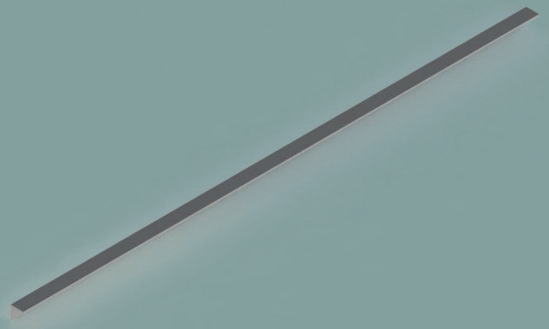
Manufacturing:

- Cut to appropriate length and TIG weld to ribs
  - No need to bend tubing, this gives highest strength

INTERNAL STRUCTURE - STRINGERS

Functionality:

- Provide additional support around passenger cabin space



Material:

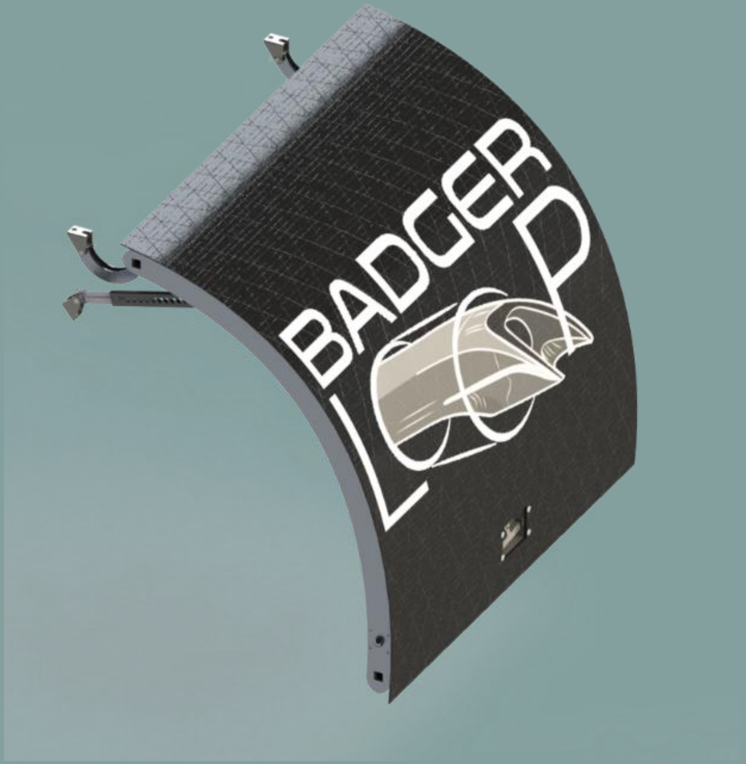
- 1" x 1" x 0.125" 6061-T6 Aluminum Angle

Manufacturing:

- Cut to appropriate length and TIG weld to ribs

INTERNAL STRUCTURE - DOOR

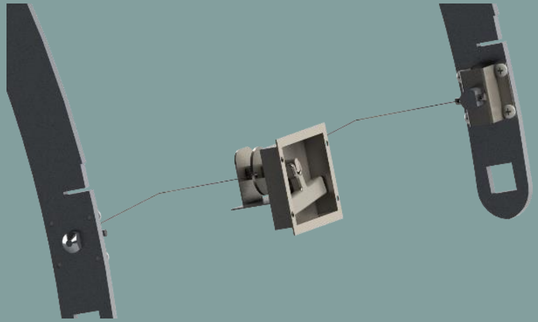
- Allows for passenger and service entry to pod
- Ratchet allows door to remain open without being propped
- Lock on the side of door ensures that it does not come open while running



INTERNAL STRUCTURE – DOOR COMPONENTS

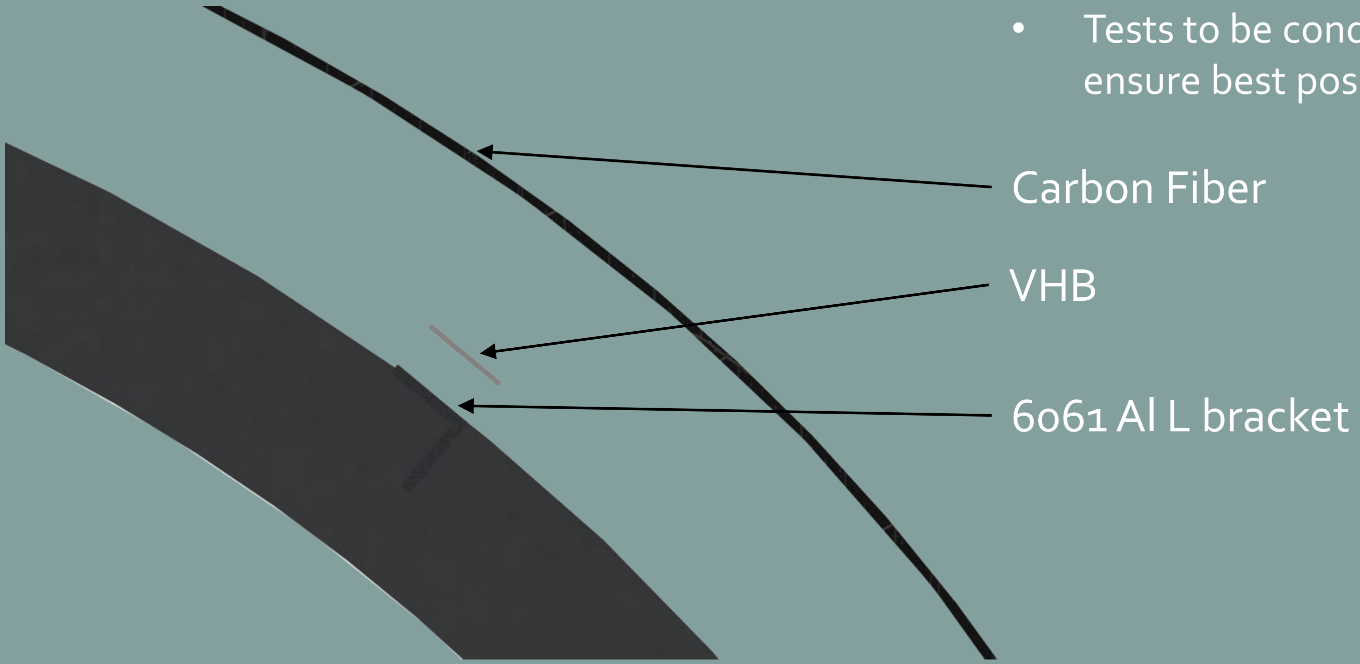
- Components:
  - 0.375" Aluminum partial rib sections
  - 1" x 1" x 0.125" Aluminum Angle supports
  - Carbon fiber outer shell
  - Dual aluminum hinges welded to frame
  - Dual aluminum ratchets hold door open

  - Handle manipulates pegs which lock door closed



STRUCTURE AND SHELL INTEGRATION

- Very High Bondage Tape (VHB) will be used to attach 6061 aluminum stringers and longerons to the prepreg carbon fiber shell
- Tests to be conducted by OEM, 3M, to ensure best possible bond

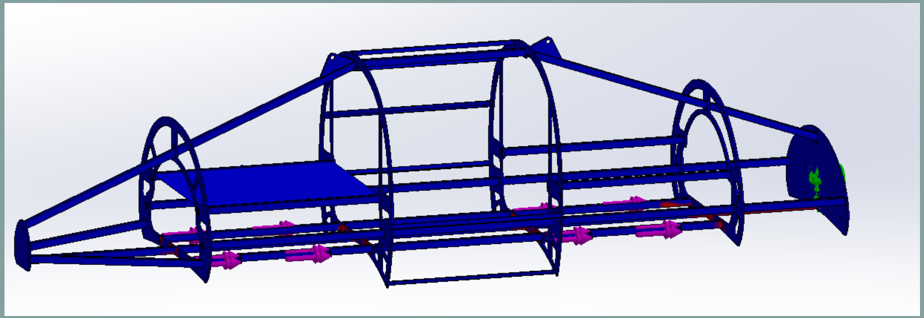


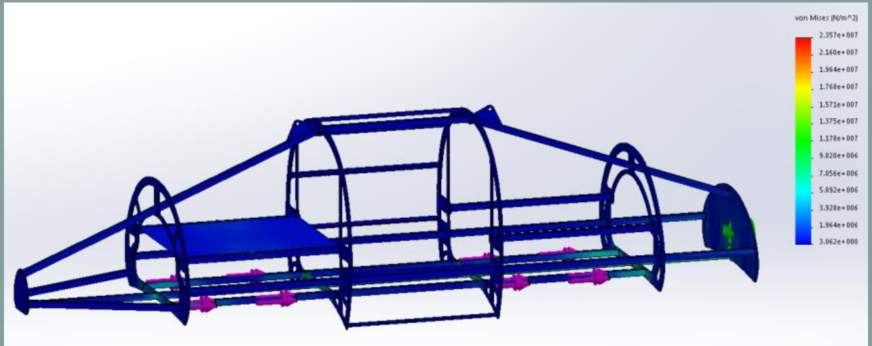
INITIAL ACCELERATION

Assumptions:

- Static Loading
- Fixed at the the Accelerator Interface
- Applying Worst Case Drag of Halbach Arrays: 2200N

There is a minimum FOS of 1.43





CRANE LIFTING POD

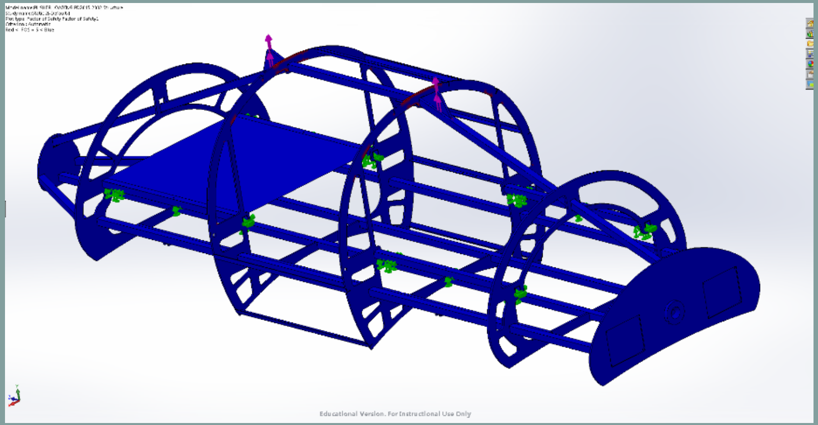
Assumptions:

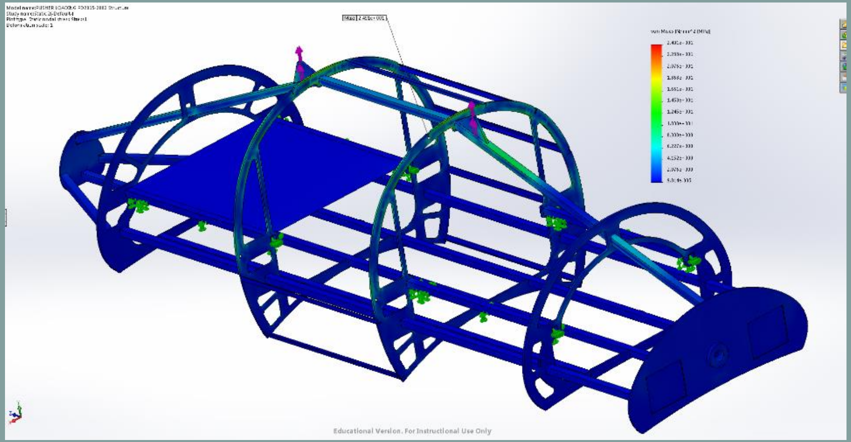
Static Loading

Fixed at the the Crane Mounting Points

Carrying Weight of Pod: 10000 [N]

There is a minimum FOS of 2.21





INTERNAL STRUCTURE WEIGHT

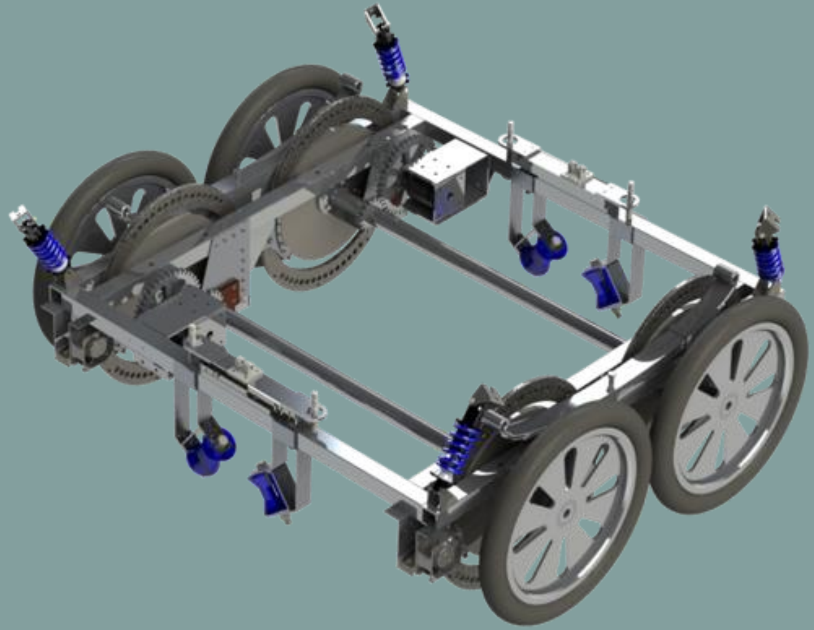
Internal Structure Materials	Mass [kg]	Cost
6061 Aluminum Ribs	49.2	$2,212.80
6061 Aluminum L Bracket Stringers	2.9	$364.48
6061 Aluminum Longerons	35.7	$272.50
TOTAL:	**87.8**	**$2,849.78**

BRAKING AND SERVICE PROPULSION SYSTEM

Two "Bogies", Four axles, eight wheels total

Consists of Several Subsystems:

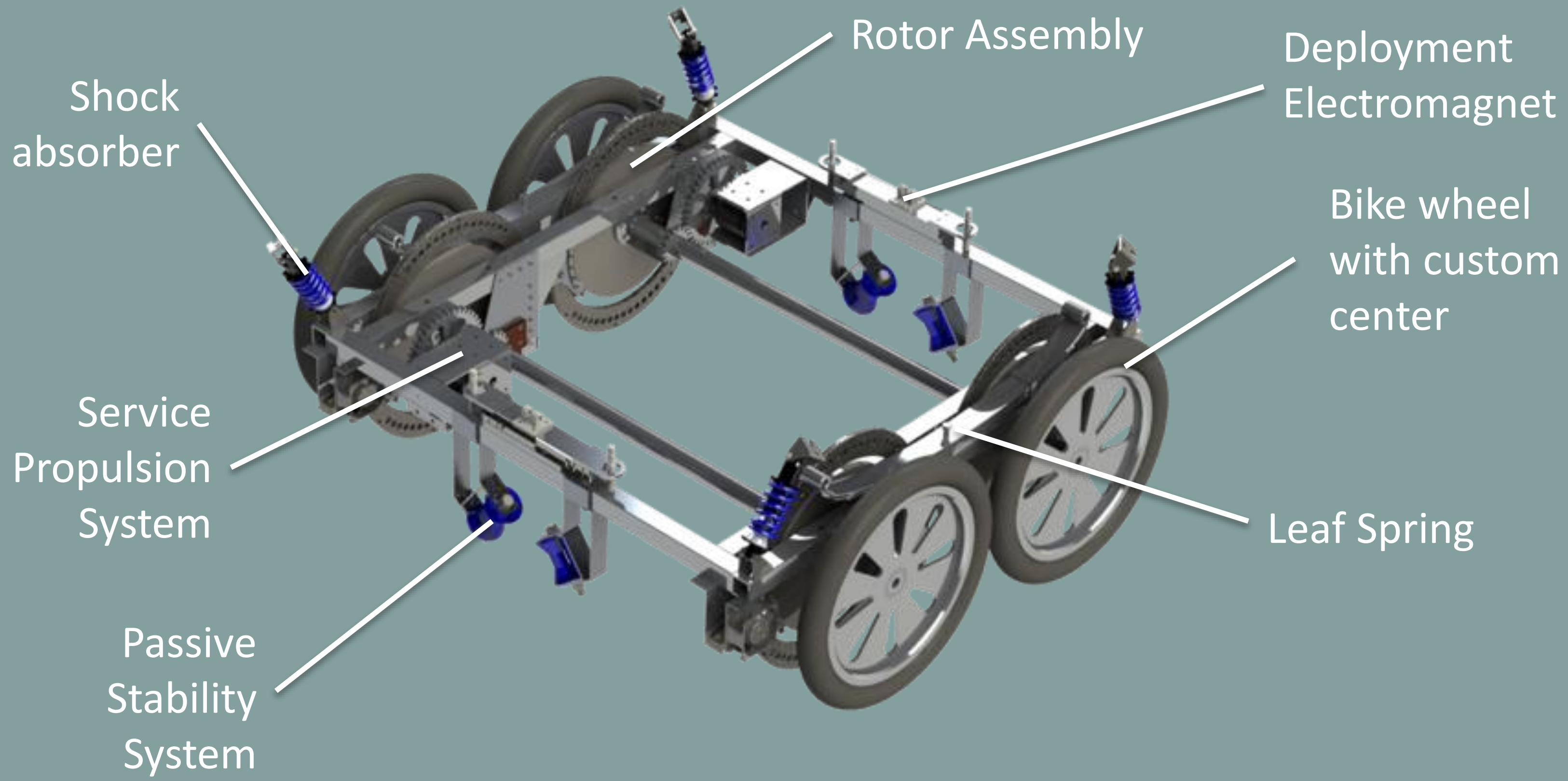
- Eddy Current Braking System
  - Two rotors and two electromagnets per axle provide non-contact braking
- Self-Locking External Drum Braking System (2LS)
  - Short-shoe external drum brakes for emergency situations
- Service Propulsion System
  - Can drive pod to end of tube in emergency
- Deployment System
  - Lifts wheels during travel and lowers them for braking



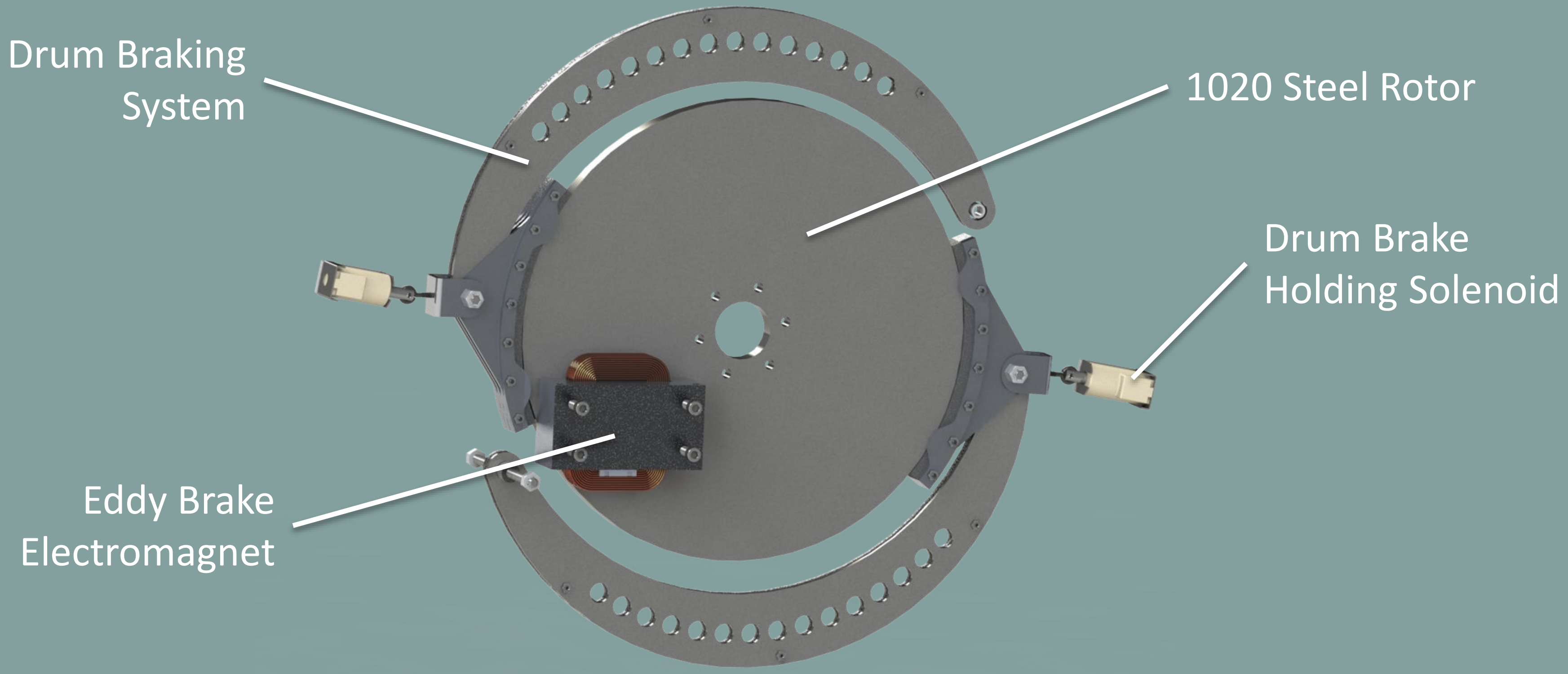
BRAKING AND SERVICE PROPULSION WEIGHT

Braking and Service Propulsion System	Mass [kg]	Power [W]	Cost [$]
Axle Assemblies	101.94	-	1159.41
Drum Brake Assembly	2.33	320	1992.00
Deployment System Assembly	73.4	10	1558.96
Service Propulsion System	6.8	9200	1151.92
TOTAL:	**184.47**	**9530**	**5892.29**

BRAKING AND SERVICE PROPULSION SYSTEM BOGIE

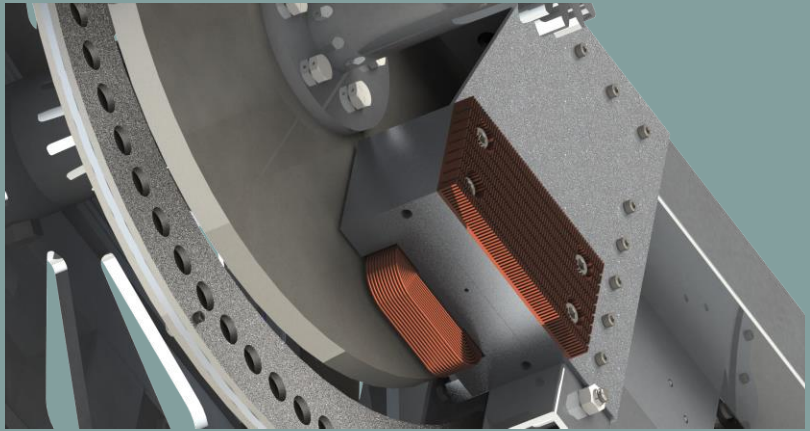


BRAKING SYSTEM ROTOR ASSEMBLY



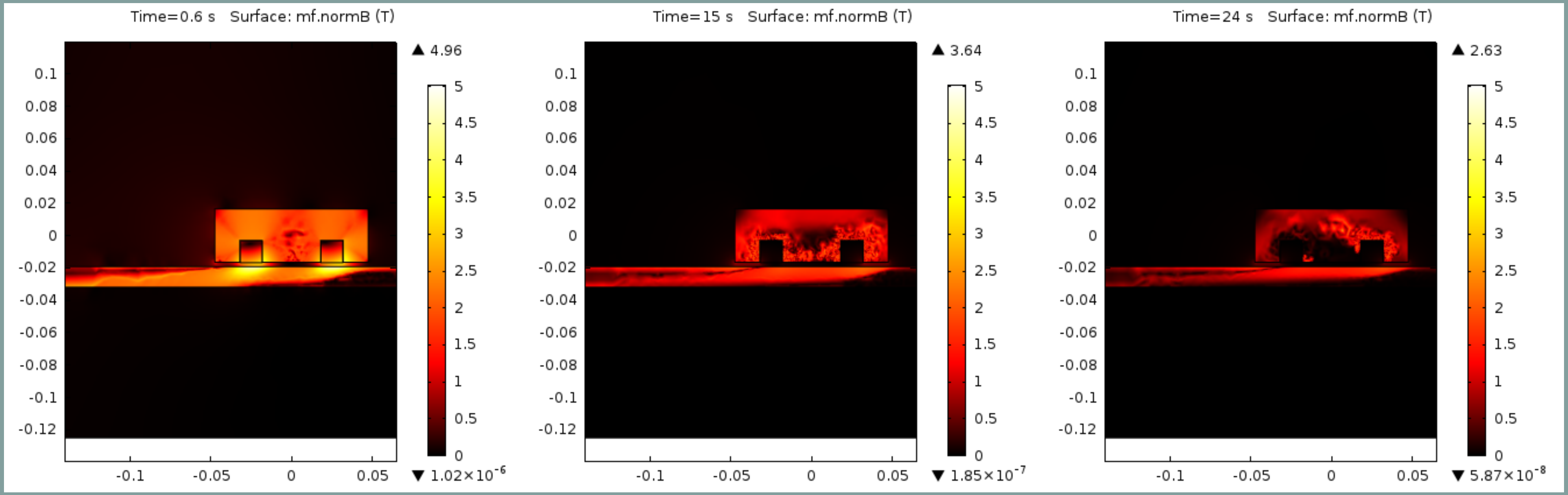
EDDY BRAKE SYSTEM

- Design consists of one Direct Current Electromagnet paired with one 1020 Steel rotor per wheel
- Power is generated from rotational motion of the shaft via the same motor used for Service Propulsion System
  - Single motor per shaft draws enough power to supply two DC Eddy Brake Electromagnets
  - At peak current, motor draws approximately 300 [W]
  - Small amounts of torque created from generating this power add to the total stopping power of the system
- Magnetic field creates an eddy current in the steel disc, opposing the motion of the electromagnet
  - Eddy current dissipated as heat
- Braking torque, current modeled with COMSOL Numeric Simulation and verified with hand calculation
  - Aluminum rotors yield better stopping at low speed
  - Steel rotors yield better stopping at high speed
  - Steel rotors chosen for overall system performance



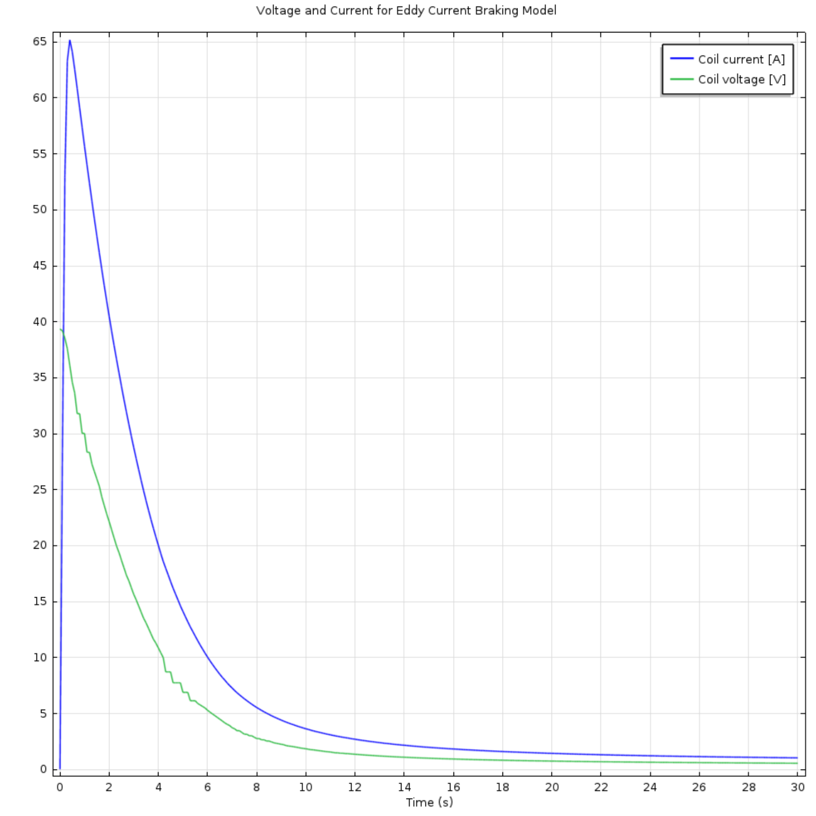
EDDY BRAKE SYSTEM MODEL

- Simplified time-based model consisting of Dynamic Model of the Pod coupled to Service Propulsion Motor (generator) model
- -2 [g] Max deceleration at full braking



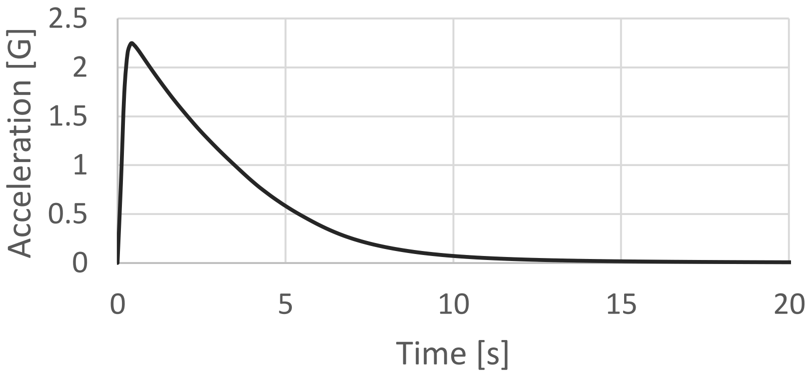
EDDY BRAKE SYSTEM MODEL

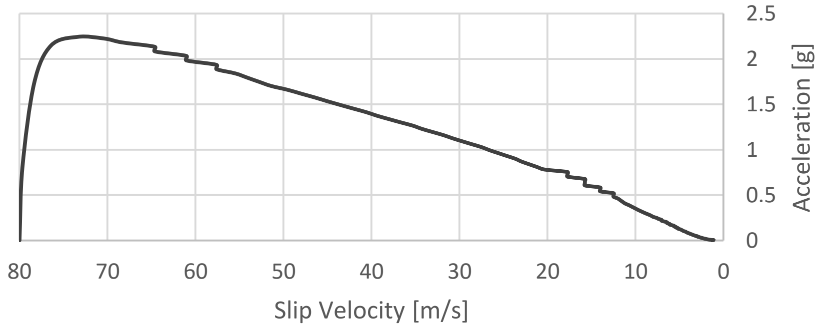
- Simplified Dynamic Model of the Pod coupled to Service Propulsion Motor model for output voltage, and therefore magnet current
- As the pod slows, less voltage is generated leading to less current flowing through the electromagnets
  - Reduces stopping acceleration until the end of the tube
    - Results in a gentle stop
- Peak current 40 [A] at highest velocity



EDDY BRAKE MAXIMUM TRAJECTORY

- Trajectory can be modulated with active control
- Trajectory graph (on right) represents the highest intensity stopping force that can be attained using braking system
- A more comfortable deceleration profile will be chosen for competition



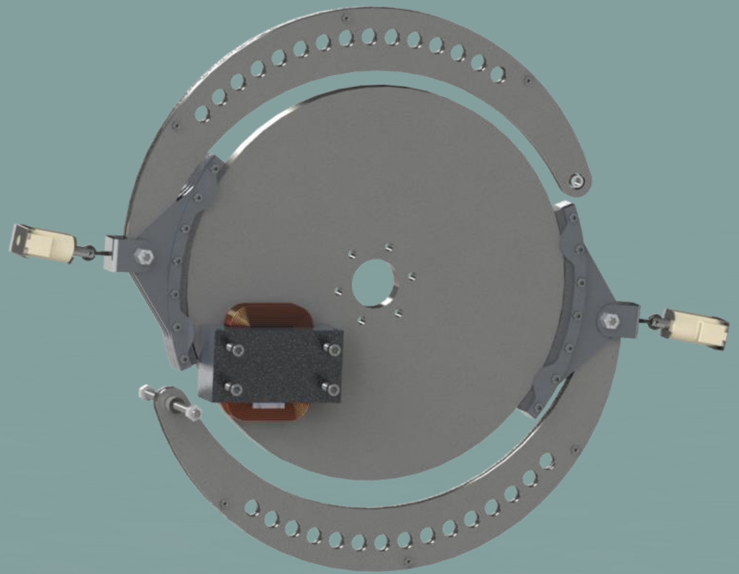


EDDY BRAKE MANUFACTURING

- Eddy brake magnets based around cores from Microwave Oven Transformers (MOT)
  - Rewound to 800 turns with 14-gauge wire
  - Packing efficiency of approximately 40% is required
- Mounted to aluminum block and copper heat-sink fin assembly to provide passive cooling under high amperage loads
  - Transient nature of loading means that the wire can be loaded far over its rated capacity to short bursts with no ill effects
  - Testing will be performed at high amperage to ensure that the eddy brakes survive at least twice the expected peak amperage of braking procedure

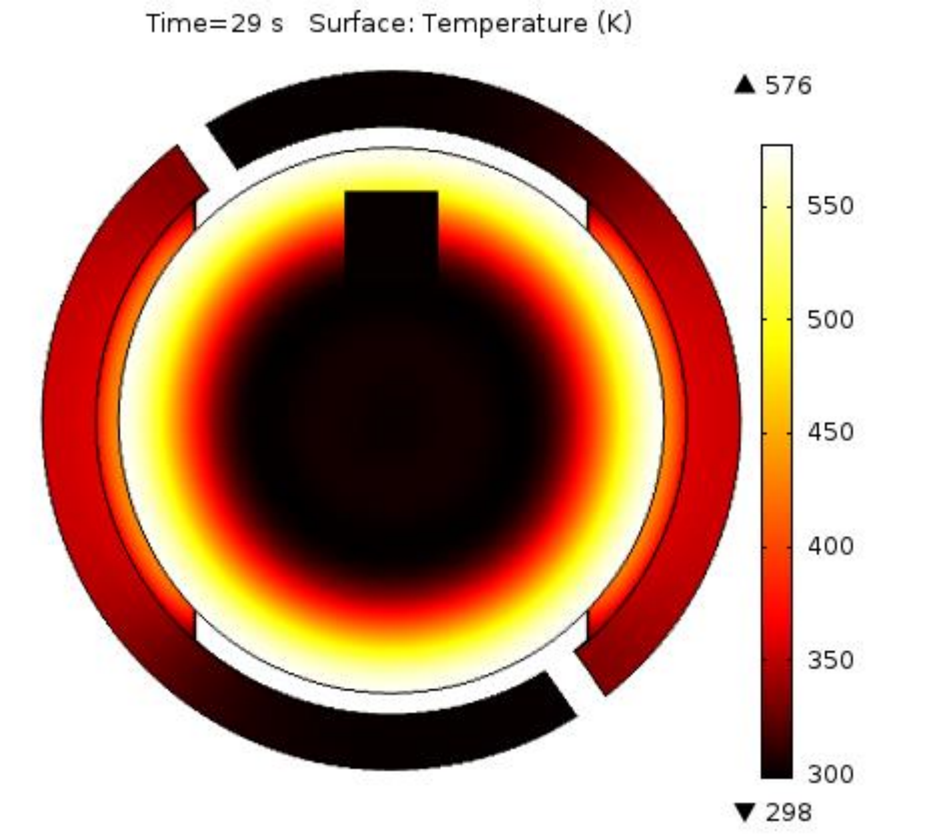
DRUM BRAKE SYSTEM

- Twin Leading-Shoe (2LS) Self-Locking External Short-Shoe Drum Brake System
  - The friction of the brake shoe pulls it further into the rotor, locking the shoe in position and providing fail-safe stopping power
- Two Solenoids hold the drum brake shoes off of the rotor when energized
  - Power failure or cutoff signal pushes drum brake shoes into rotor
- Designed for a single emergency use only
  - Will require complete replacement of the brake pads after use



DRUM BRAKE SYSTEM THERMAL MODEL

- Modeled with simplified geometry to verify temperature of brake pads
  - Brake fade will likely not be an issue with the material we are using
- Peak temperature occurs after 29 seconds of braking
- No radiation heat dissipation taken into account due to potential reflectivity of surfaces around the brake disc
- Ceramic compound brake shoes will actually increase friction coefficient with temperature
- Rotor max temperature: 576 [C]



DRUM BRAKE MANUFACTURING

- The drum brake assembly will be custom built and assembled in house
  - Brake arms will be cut from 4x4 steel plate with waterjet cutting machine
  - Brake Pads will be made from sintered metal and ordered from McMaster-Carr
- Two drum brake assemblies will be placed around each rotor and mounted on to the central frame
  - Axle will remain removable for servicing once drum brakes are installed
  - Drum brake arms designed to pivot, providing easy access to axle bearing mounts
- Testing will be carried out on all-up frame assembly to verify functionality of drum brakes

BRAKING FAULT TOLERANCE

1) Loss of Axle

- Can sustain loss of any two rotors without reduced braking capacity
- Can lose one rotor per axle without asymmetric braking
- Loss of any two axles reduces braking capacity to half

2) Skid Condition (Track Surface Contamination)

- Eddy current brakes will be Pulse-Width Modulated (PWM) to provide anti-lock braking
- Drum brakes will not be able to modulate amount of braking force, in this case a skid condition is induced
  - Because this system cannot be modulated, it will only be deployed as systems last-resort if all other braking methods fail

3) Loss of Levitation

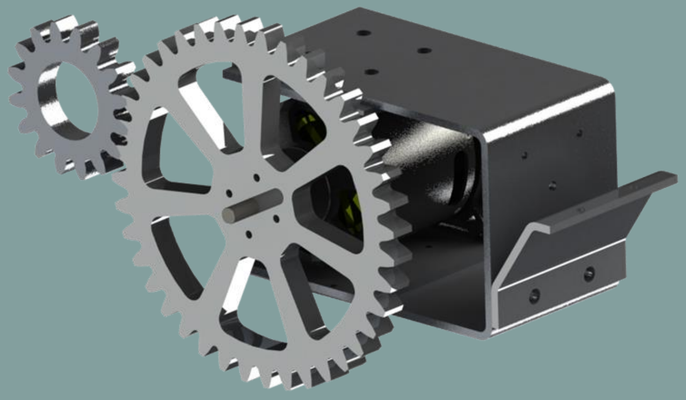
- Wheels designed to deploy within one second of power loss, passive Halbach Arrays will sustain lift due to pod velocity
- Wheels will deploy if pod loses lift and contacts ground
- Axle suspension system will still provide shock absorbance for impacts when stowed

4) Loss of Power

- Emergency drum brake system held in place by electromagnets powered by central battery
  - Each brake will engage if pod system loses power
- Deployment system will automatically release on loss of power

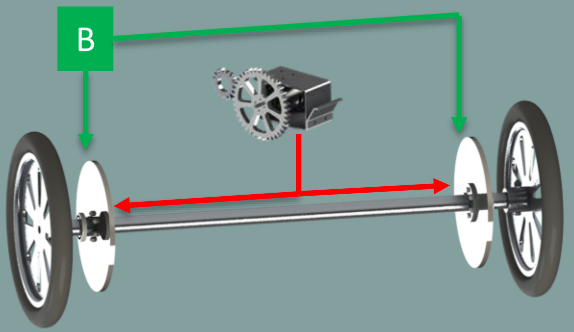
SERVICE PROPULSION SYSTEM

- Gear Ratio of 0.6 for maximum current to eddy braking system
- During service propulsion the motor draws nearly 100A at peak load
  - One dedicated battery string per motor
- 3-phase AC motor with commercial Electronic Speed Controller (ESC)
  - ESC will convert DC power into modulated AC waveform to drive poles of motor
- Waterjet cut gears will provide power transmission to and from the axle

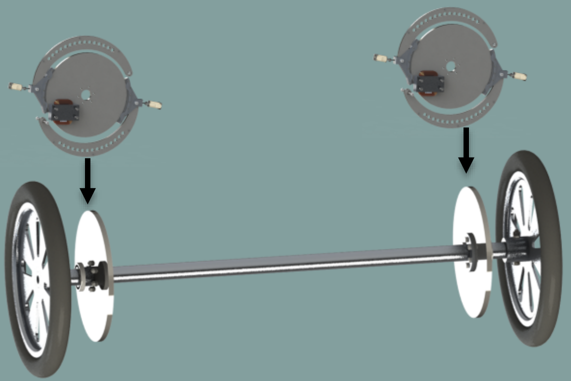


BRAKING SYSTEM POWER FLOW

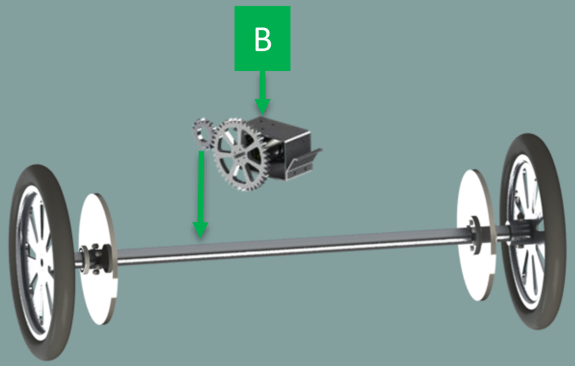
Normal Braking: Regenerative motor powers eddy brakes and battery prevents drum brakes from engaging



Emergency Braking: Requires no power supplied anywhere, drum brakes engage

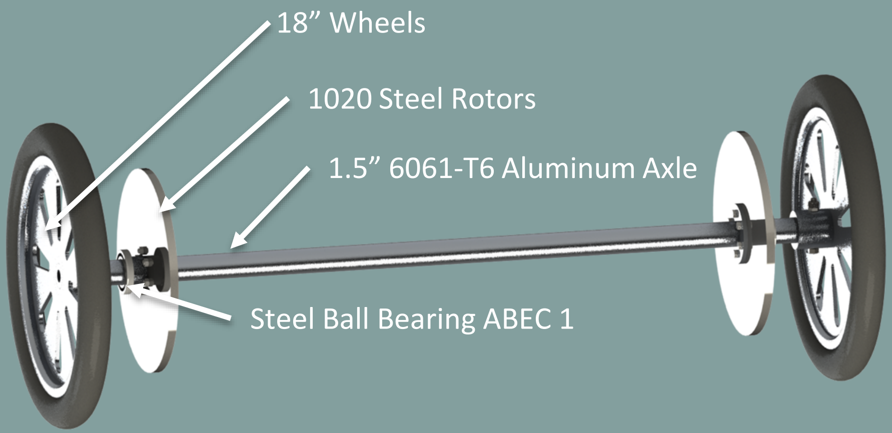


Service Propulsion: Battery Sends power to motor



AXLE ASSEMBLY

- Hollow 6061-T6 Aluminum Axles used for weight savings
- 1020 Steel Rotors used solely for braking
- Wheels will be machined with a waterjet cutter
- Overall Dimensions
  - Axle length: 47 in
  - Wheels: 18 in

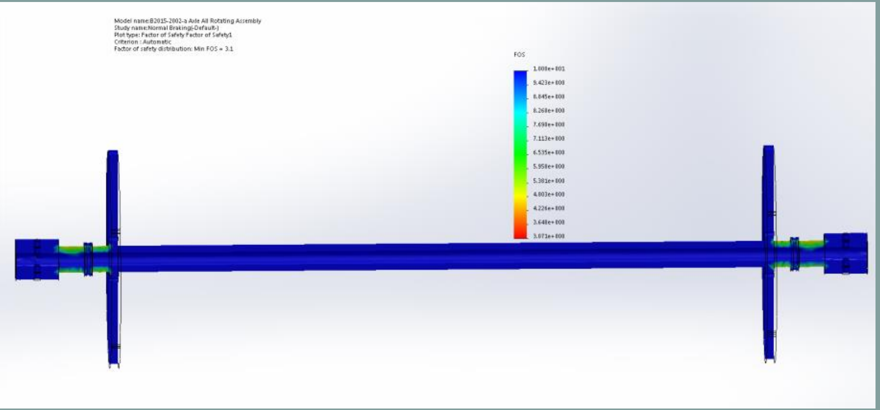


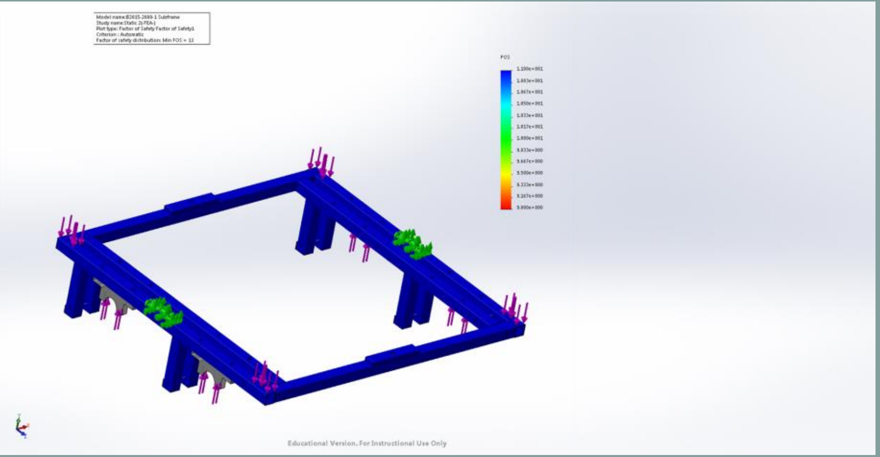
ANALYSIS SCENARIO: NORMAL BRAKING

- Axle and Sub-frame assemblies statically loaded with half of the pod mass to verify structural integrity

- Axle Assembly found to have a minimum Factor of Safety of 3.1 and the Sub-frame was found to have a minimum Factor of Safety of 10.0

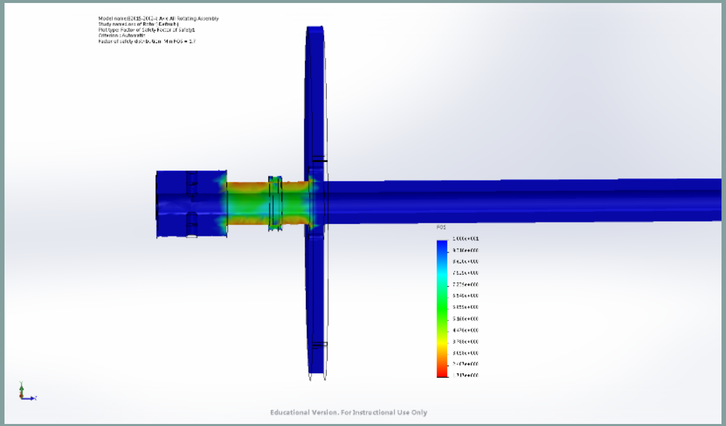
- For normal braking conditions, the pod is structurally sound and safe

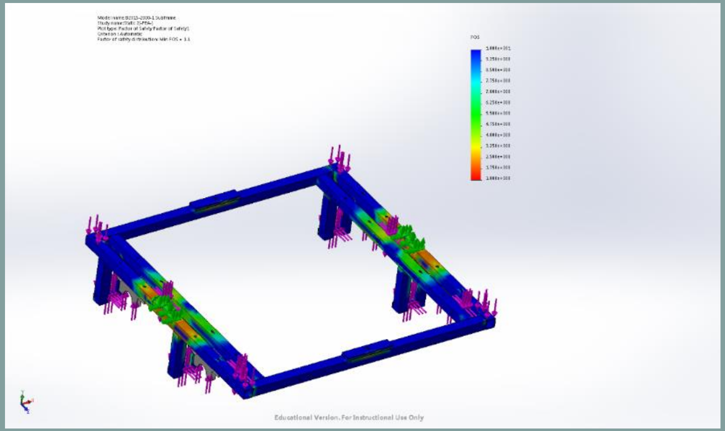




ANALYSIS SCENARIO: EMERGENCY BRAKING

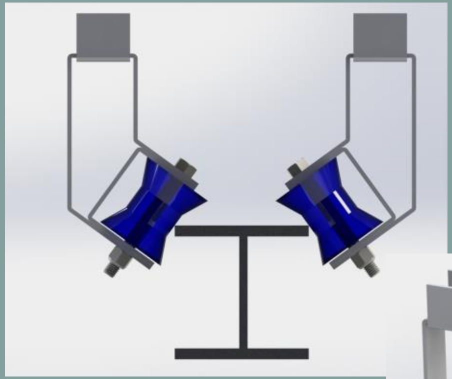
- Axle and Sub-frame assemblies statically loaded with half of the pod mass in addition to the moments caused by fully engaging the drum brakes
- Axle Assembly found to have a minimum Factor of Safety of 1.7 and the Sub-frame was found to have a minimum Factor of Safety of 1.1
- Fatigue analysis not performed, worst case emergency scenario only
- Pod is capable of withstanding a power failure/emergency braking scenario

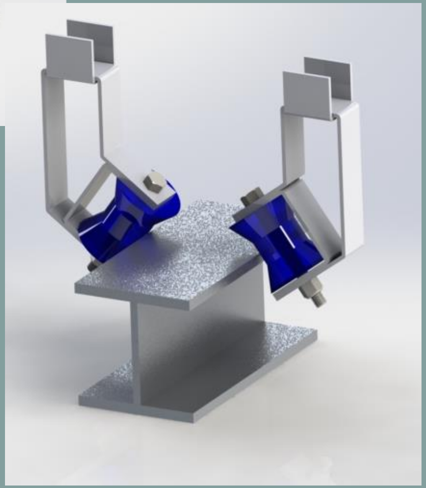




STABILITY MECHANISM

- High performance roller bearings on center rail provide lateral stability
- Passive system
  - Four roller bearings per braking bogie
- Dynamic Load Capacity: 6005 [N]
- Max Rated Rotational Speed: 25,000 [RPM]
- Self-centering and can accommodate slight fluctuations in pod trajectory

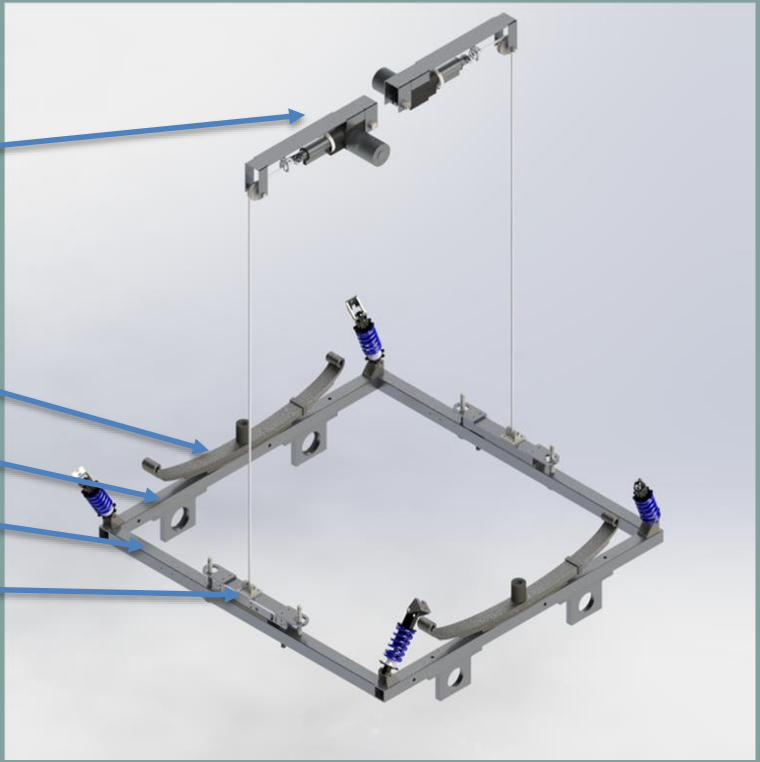




DEPLOYMENT SYSTEM OVERVIEW

For each of the two wheel bogies:

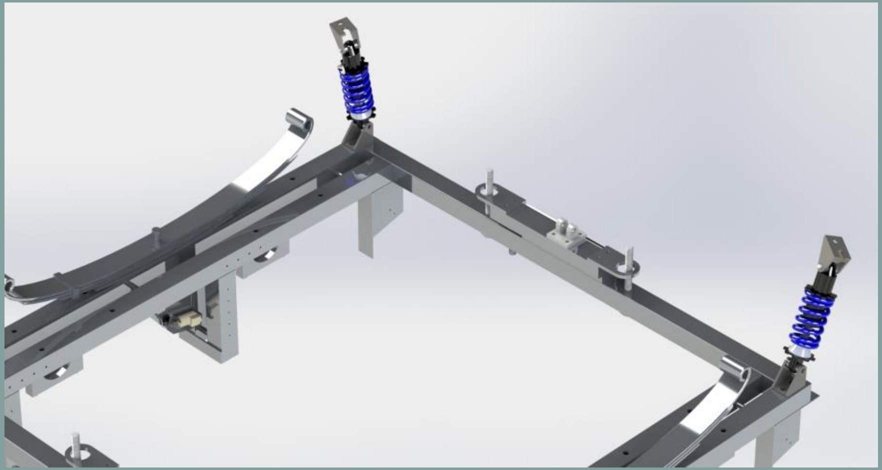
- Two 3” linear actuators per frame
- Two leaf springs per frame
- Four shocks per frame
- Aluminum sub-frame: 39.43” long, 41” wide
- Two electromagnet locks per frame



DEPLOYMENT SYSTEM OVERVIEW

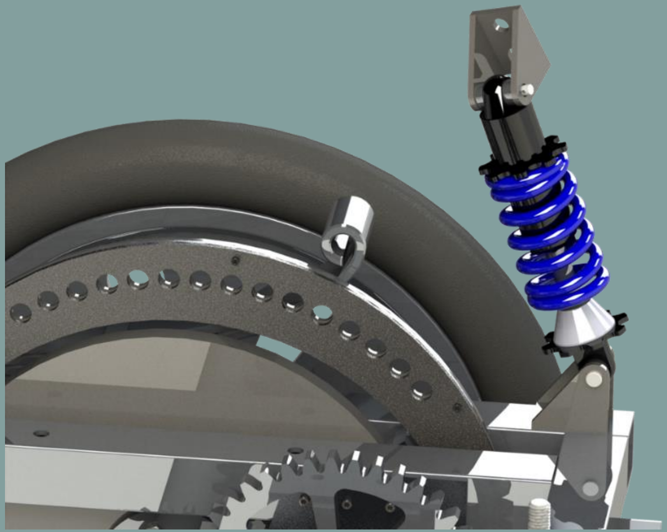
- Linear actuator raises and lowers the wheel assembly 1" when braking is required
  - Actuator cable is attached to the electromagnet locks positioned on the assembly

- Manufacturing:
  - Actuator mounts
  - Magnetic lock guides
  - Shock and leaf spring mounts
  - Magnet mounts



SUSPENSION MECHANISM

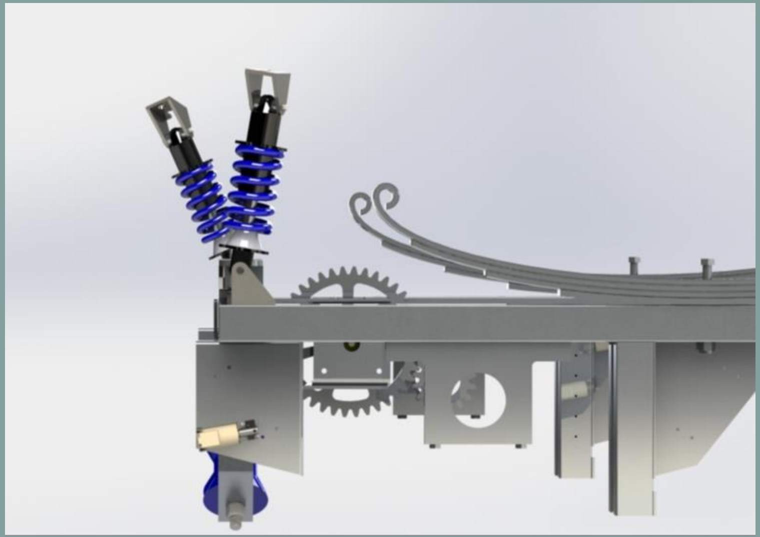
- Leaf springs will carry the majority of the pods mass
  - Ultimate Load of each leaf spring: 294.8 [kg]
  - Max Deflection of each spring: 0.148 [in]
- Factor of Safety: 6.83
- Shock absorbers
  - Used as a dampening system to avoid excess oscillations
  - Rated for 75-100 [kg]
- Safety Measure
  - Rubber stopper prevents wheel assembly over excursion



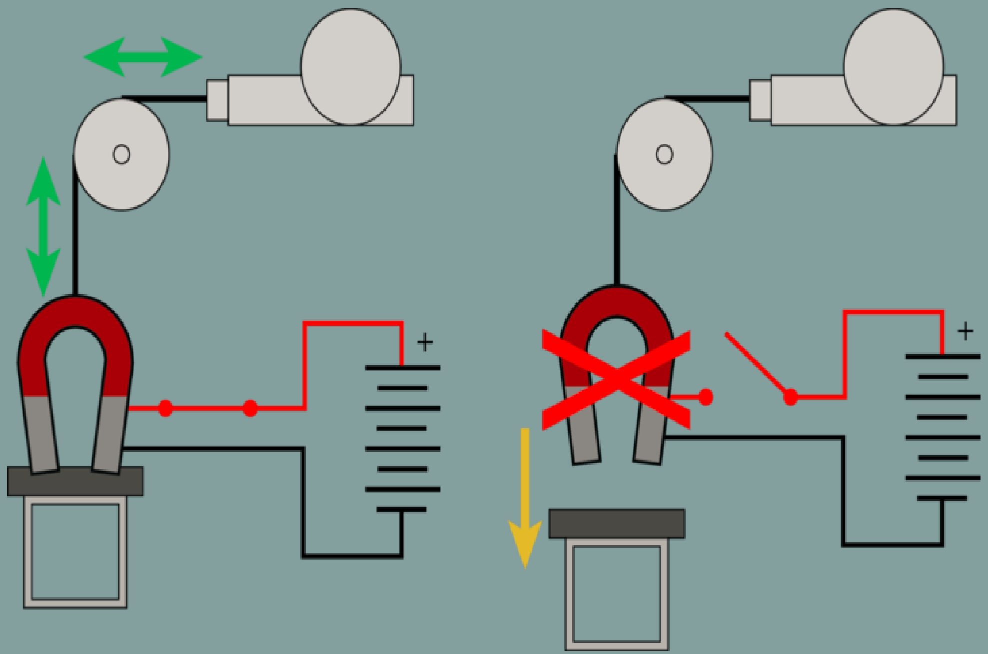
BRAKING TO POD INTEGRATION

- Per Wheel Assembly:
  - 4 pinned connections attached to frame to support the shocks
  - 2 pinned connections per leaf spring

- Linear actuators will be welded to main frame
  - Actuators wound with cable attach to electromagnetic locks
  - Lowers and raises the electromagnets which carry the wheel assembly



DEPLOYMENT FAULT TOLERANCE



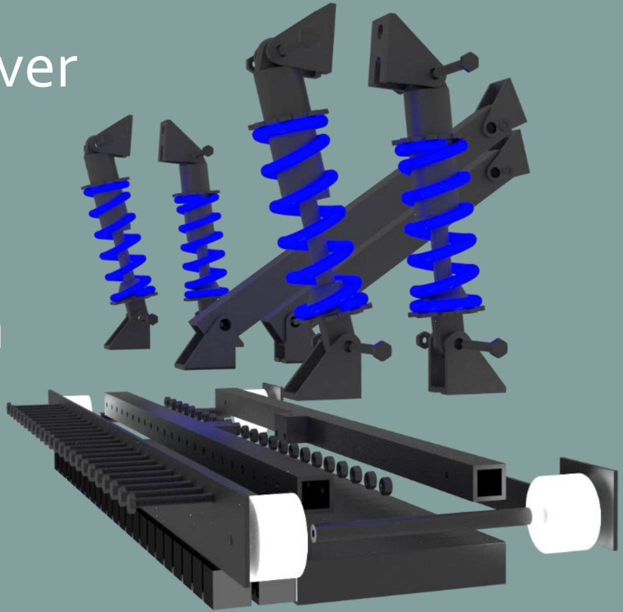
When powered nominally, electromagnet locks to the frame: linear actuator can lower and raise the wheel assembly

In case of emergency power failure, electromagnetic lock shuts off: wheel assembly drops to the ground to brake the pod

PASSIVE HALBACH ARRAY LEVITATION SYSTEM

576, 1 inch neodymium magnets provide failsafe levitation for the BadgerLoop pod while travelling over 11.2 [mph]*

System is composed of 4 levitation modules pictured right



*Based on initial modeling, can adjust after further COMSOL models are verified with empirical data

LEVITATION SYSTEM MASS

#	Passive Halbach Array System	Mass [kg]	Cost [$]
576	1 [in] N52 NdFeB Rare Earth Magents	70.3	$4,150.00
96	6 [in] Stainless Steel Tubing Sections	26.3	$405.00
16	Suspension Shock Absorber	7.1	$179.00
16	Nylon Heavy Duty Wheels & Bearings	2.2	$231.20
48	Aluminum Mounting Brackets	4.3	$336.00
4	Aluminum Structural Frame	22.5	$316.80
-	Misc. Subsystem Hardware	1.9	$177.00
	TOTAL:	**134.6**	**$5,795.00**

LEVITATION SYSTEM EXPECTATIONS

Passive Halbach Arrays

- Neodymium Iron Boron Grade 52 permanent magnets assembled inside stainless steel tubes arranged in a configuration to maximize magnetic field passing over the aluminum sub-track
- Preliminary levitated mass capability of 1200 [kg]
- Our design provides gap height of 10 [mm] (0.393701 inches) when pod is traveling at 180 [mph]

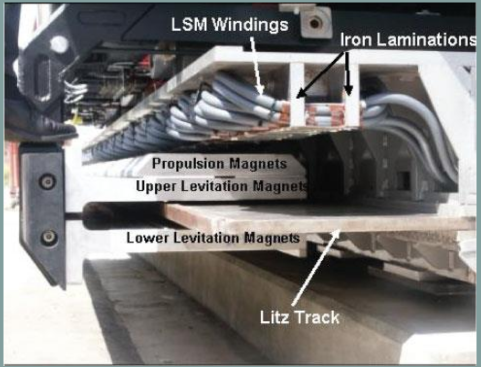
System must mitigate any vibrations introduced by imperfections presented by the track

This system is based on our design constraint of achieving at least 10 [mm] (0.393701 inches) of levitation at a velocity of 180 [mph]

LEVITATION SYSTEM SELECTION

- Powerless levitation
  - Permanent magnets require no direct power consumption to provide lift
- Passive Halbach Arrays offer failsafe method of levitation
  - In the event of power loss the system continues to perform
  - The magnetic drag induced on the arrays provides added braking in the event of power loss
  - High stiffness of magnetic field provides a cushion between the pod and the track for heightened passenger safety
- Simple configuration
  - This system has an easily adjustable modular design that can be changed to fit a wide variety of applications
    - Add more magnets while: increasing width of magnet modules, increasing length of levitation modules, adding shocks as needed, etc.
- Halbach arrays provide passive stability in pitch and roll
  - The magnetic lift force increases in strength as the arrays near the sub-track
- Air bearings less realistic in a near vacuum
  - Operating at 0.02 PSI, which provides minimal aerodynamic drag, does not have enough air mass in the tube to supply air bearings

LEVITATION SYSTEM SELECTION



**Images: http://www.ga.com/urban-maglev-*
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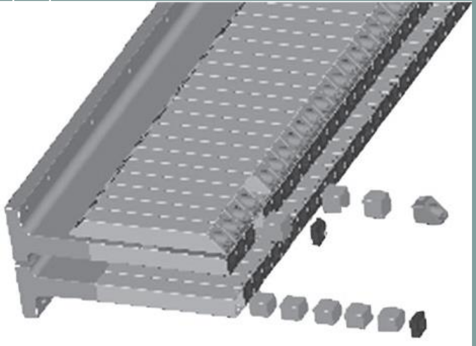


General Atomics Urban Maglev program

- Used 2" Neodymium cube magnets
  - Arranged in Halbach arrays with magnets shifted 45 degrees in orientation
- 8,500 [kg] chassis successfully levitated 30 [mm]
- Liftoff at 5 [m/s] (~11.25 mph)
- A form of Inductrack was used to improve L/D (lift to drag) ratio (compared to a single conductive plate)
  - L/D can approach 200:1 with inductrack (Post, et al. 2000)
- Utilized LSM windings (see figure left) and permanent propulsion magnets to achieve successful acceleration

HALBACH ARRAY FUNDAMENTALS

Halbach arrays are magnets oriented in such a way that the magnetic field is amplified on one side of the array and greatly reduced on the other

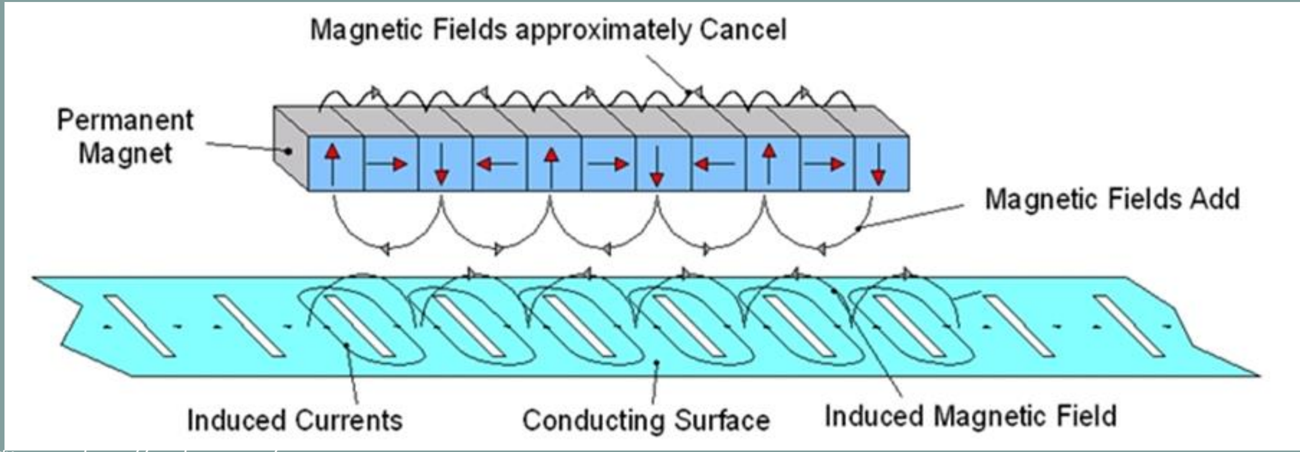


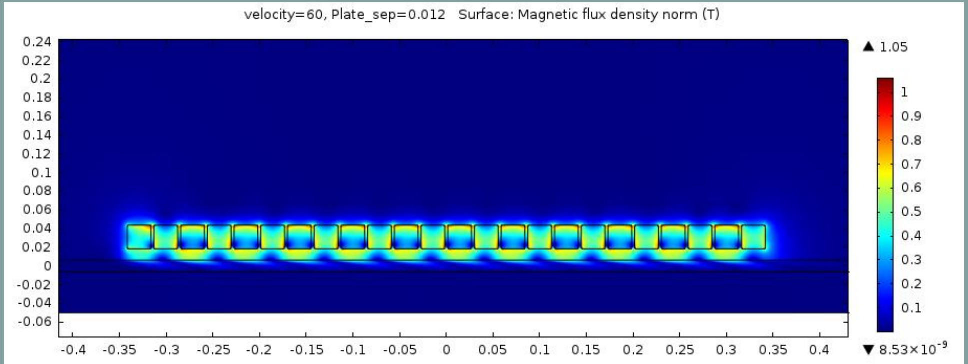
**Image: http://sunlase.com/*

When traveling over a conductive surface, eddy currents are created and thus provide lift which increase as velocity increases

*See Appendix E for more information

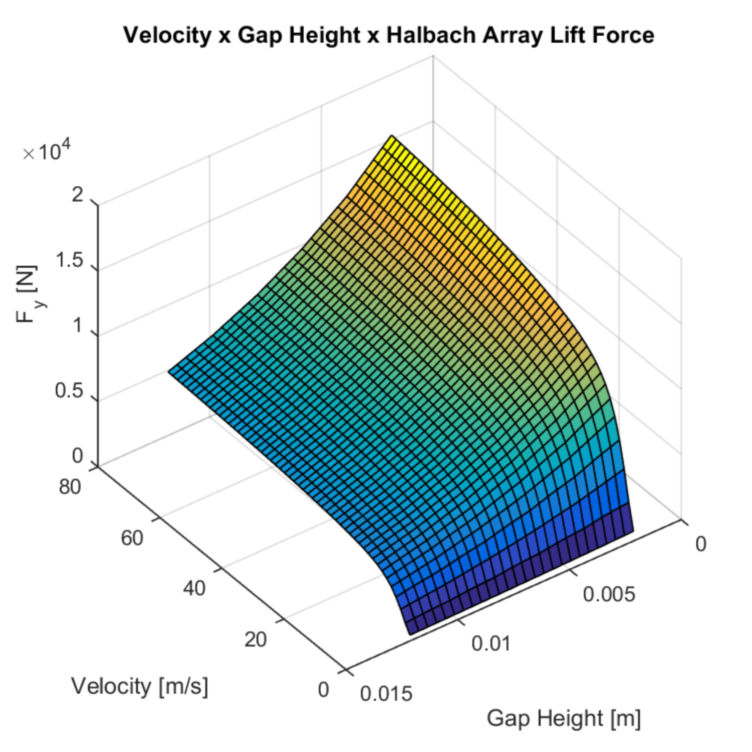
HALBACH ARRAY COMSOL SIMULATIONS

- Solved in three ways for verification of accuracy
  - Lorenz force integration over a volume
  - Line integral of the Maxwell Stress Tensor over the perimeter of a shape for both:
    - Conductive region
    - Magnet region
- Matlab used for numerical integration



Magnetic flux density rendering of COMSOL modeling of a Halbach array.

HALBACH ARRAY COMSOL SIMULATIONS



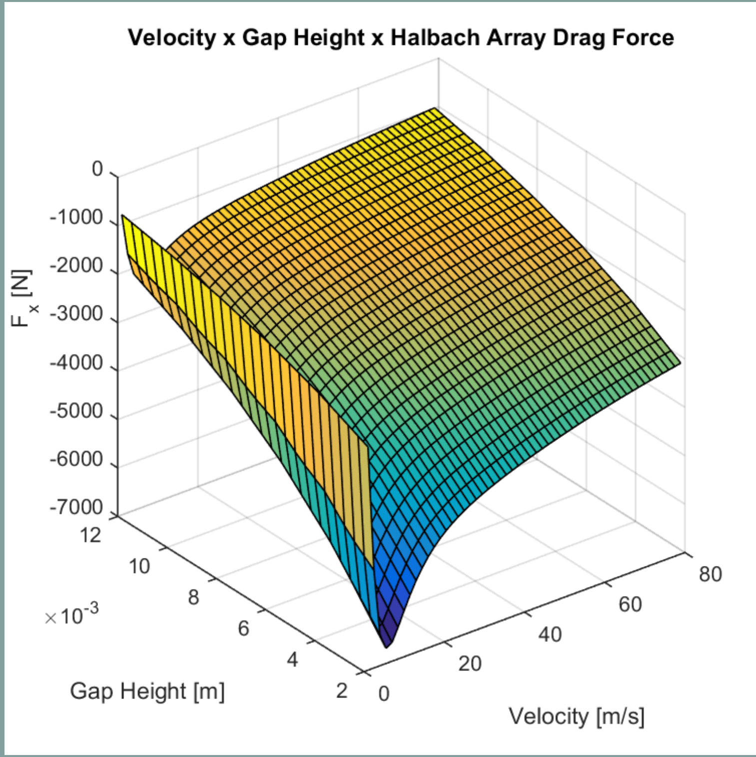
Plot of Gap x Velocity x Lift force for one single levitation module

Modeling correctly verifies the researched effect (Murai, et al. 2003) that Halbach arrays have in the use of levitating a moving vehicle

- The lift force is proportional to increasing velocity and decreasing gap height

Data from verified COMSOL numeric model (see appendix)

HALBACH ARRAY COMSOL SIMULATIONS



Plot of Gap x Velocity x Drag force for one single levitation module

Modeling correctly verifies the researched effect (Murai, et al. 2003) that Halbach arrays have in the use of levitating a moving vehicle

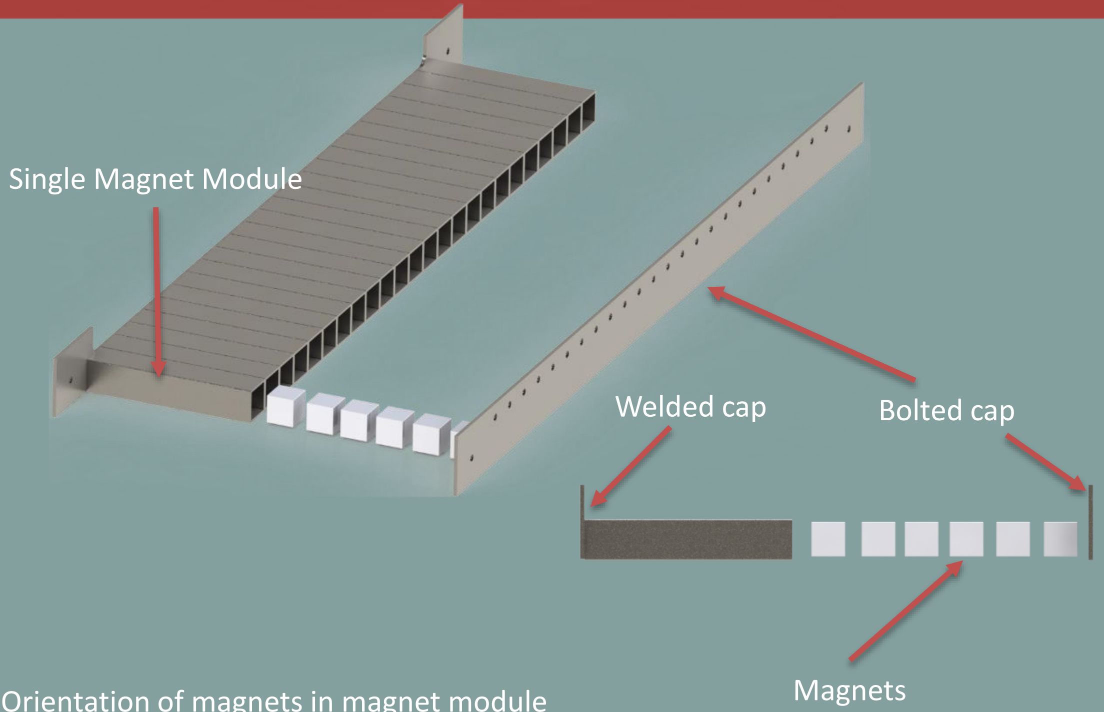
- Drag force is inversely proportional to increasing velocity and gap height

Data from verified COMSOL numeric model (see appendix)

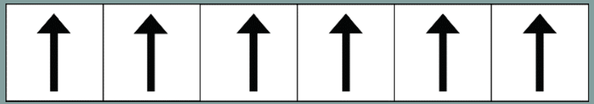
HALBACH ARRAY MODULE DESIGN

- Levitation system comprised of arrays of magnet modules (pictured right) and levitation modules

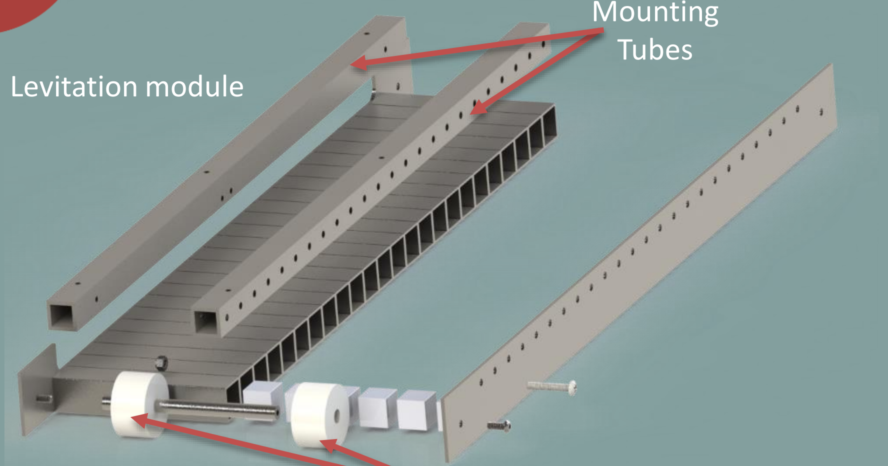
- Using simple metal tubing and caps allows for easy modular scaling modifications or design changes

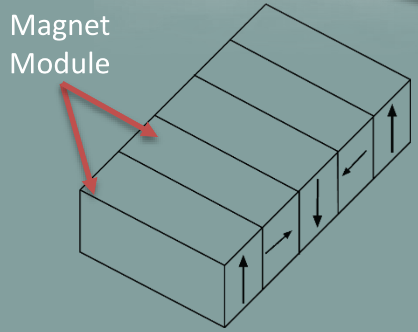


Orientation of magnets in magnet module



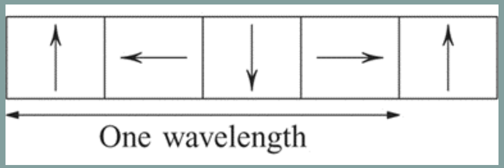
HALBACH ARRAY MODULE DESIGN





Visualization of Halbach array in Levitation module

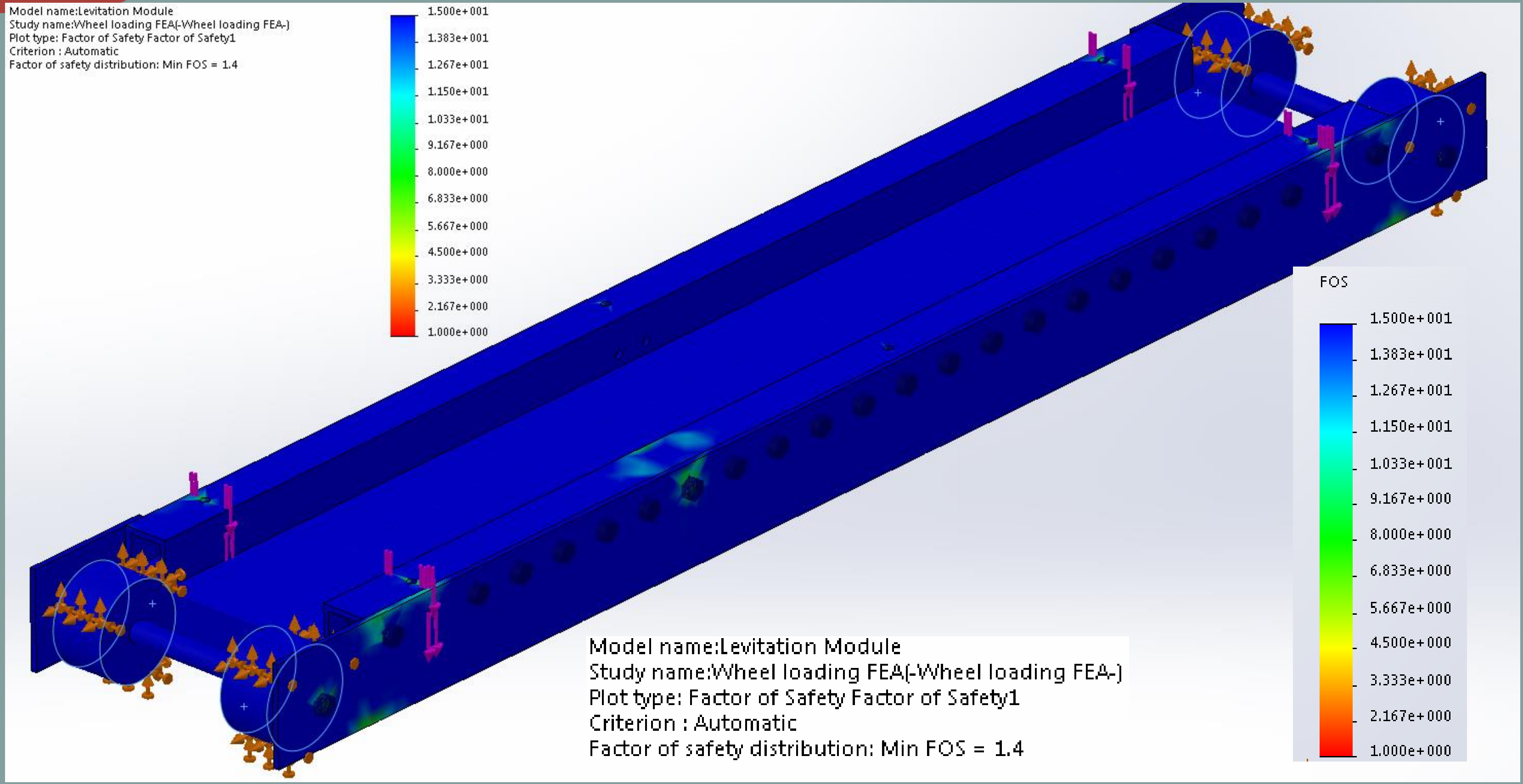
Depiction of Halbach array wavelength



- Levitation module (pictured left) is made up of 24 magnet modules

- Creates 6 wavelengths of Halbach arrays for a total length of 28.35 inches per array

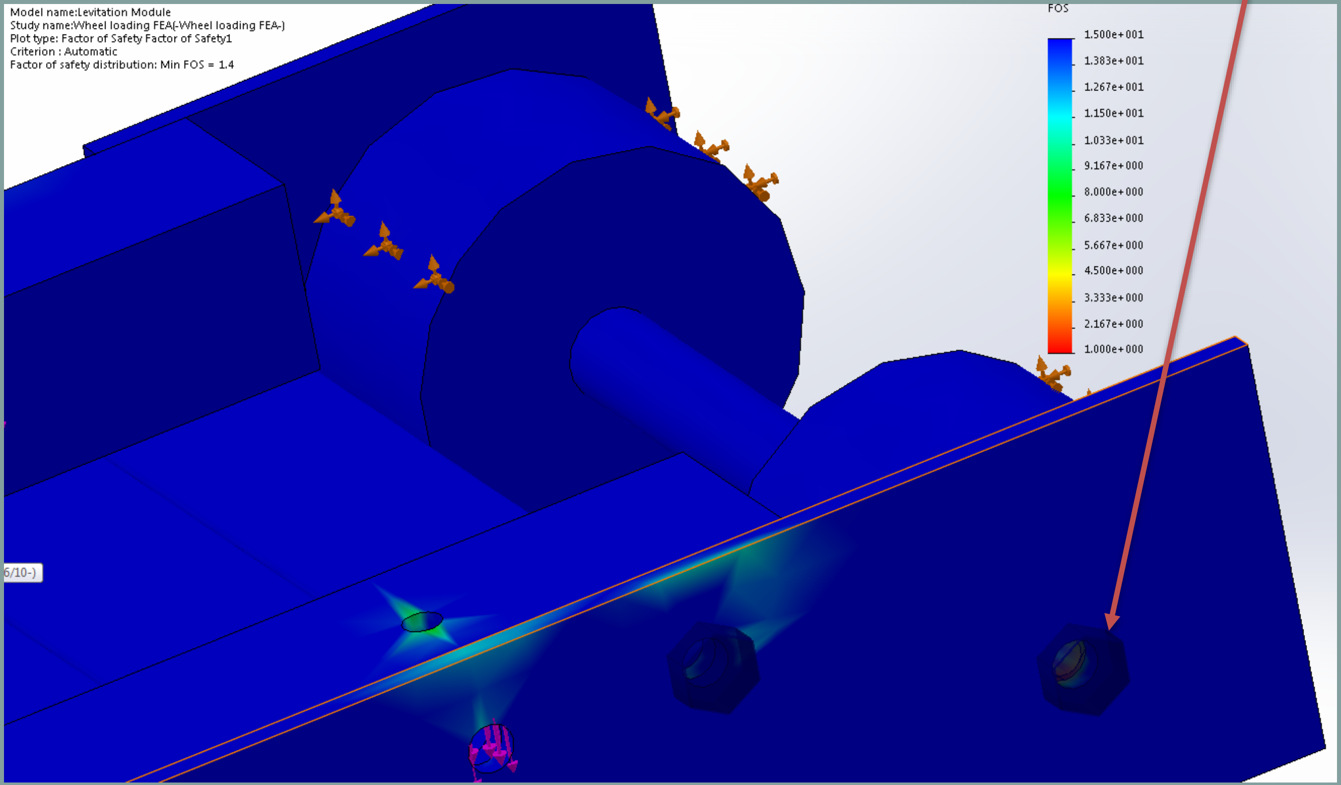
HALBACH ARRAY MODULE DESIGN

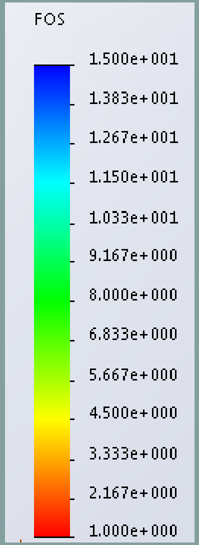


Nearly all of the material under stress during the rolling acceleration phase has a FOS (Factor of Safety) greater than 10

HALBACH ARRAY MODULE DESIGN

Min FOS location





Seen left, the minimum FOS of 1.4 occurs in a centralized location: the edge of the threaded hole of the axel

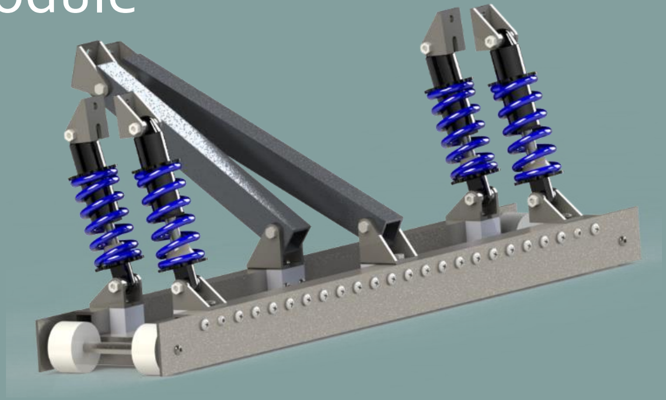
- Working to improve this aspect of system design

Model name:Levitation Module
Study name:Wheel loading FEA(-Wheel loading FEA-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 1.4

PRECAUTIONARY ROLLERS

- High load-bearing nylon wheels mounted to the magnet modules provide the pod with a low-friction rolling alternative until the pusher accelerates the pod to the liftoff speed

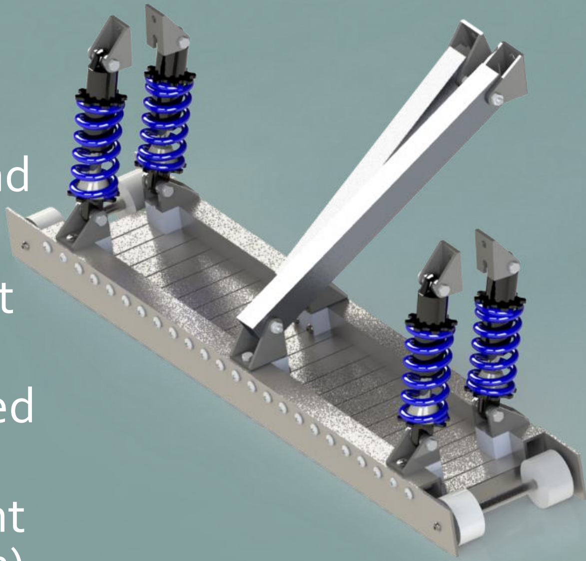
- Nylon wheels extend 2[mm] (0.08 inches) beneath the bottom of the levitation module



LEVITATION SYSTEM SUSPENSION SYSTEM

Each Halbach Array has a suspension system attached to the frame of pod

- 4 spring and damper shocks allow for smooth ride
- Shocks rated for 75-100kg each
- Two control arms keep movement in desirable direction and keep the module parallel to the ground
- Allows vibrations to be absorbed
- Passive roll and pitch stability by placing modules at each of the four approximate “corners” of the pod
- This suspension extends outwards when compressed which adds to roll stability
- Simple design able to accommodate variable weight (add more shocks) and size (vary control arm length)



FAIL-SAFE LEVITATION MECHANISMS

Halbach arrays provide a fail-safe levitation

- In the event of power loss, the Halbach arrays will sustain levitation long enough for the wheels and emergency brakes to deploy
- Passive arrays provide redundancy to pod's braking system with their inherent drag
- Passive roll and pitch stability
  - As the modules get closer to the sub-track, the lift force gets stronger
- Halbach arrays are mounted to ensure the pod stays above the center rail and keep out zone and once its shocks are fully compressed it will touch down to ride on wheels at the bottom of the module

Nylon Wheels

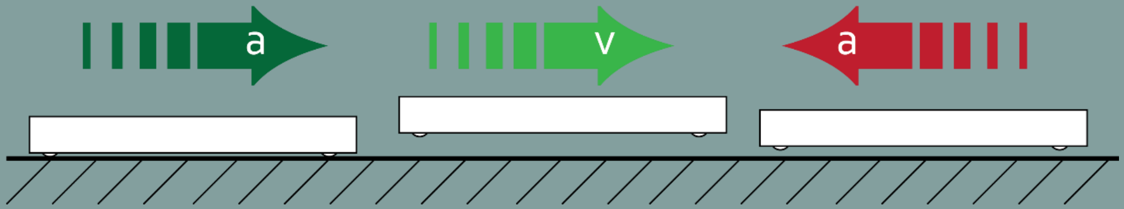
- Wheels will sit 2[mm] (0.08 inches) below array module to roll on when the pod is being accelerated by the SpaceX pusher
- Approximately 1/5 the gap height to allow for levitation

LEVITATION SYSTEM PERFORMANCE AND OPERATION

Operation

1. Rest on nylon wheels until accelerator pushes pod to 11.2 [mph]
2. Levitation is sustained over the length of the track
3. When reaching the end of the tube, Halbach wheels stop spinning, wheeled braking engages, and the arrays' drag aids in slowing down the pod until the braking system comes to a complete stop

1) a = 1.5g 2) v = ~180 mph 3) ~2000N drag force due to Halbach arrays



ARRAY MODULE ASSEMBLY

Manufacturing procedure

1. Weld magnet module tubes together and to a back cap without magnets in them as magnetism will degrade at the max operating temperature and completely demagnetize at the curie temperature
2. Weld mounting tubing on top of (now empty) levitation module
3. Separately assemble control arms and shocks
4. Square non magnetic stainless steel tubing will be slid into a loading device and have bolted cap placed at the edge of open end
5. Magnets will be inside 1” square aluminum tubing all in the same orientation
   - This tube will be aligned with next open stainless steel magnet module tube
   - A pusher rod will plunge the preloaded magnets into the module
   - The bolted cap will be unbolted, moved forward one space, and bolted again
6. Once all magnets are in and bolted cap is secure, attach shocks and control arms
7. Each levitation module will be constructed and then await the full construction of the pod to finally get mounted last
8. There are many safety concerns with such powerful magnets in place, thus mounting will be the final step

PASSIVE HALBACH ARRAY LEVITATION SYSTEM MANUFACTURING

- Magnetic modules will be constructed using non-magnetic materials
  - Stainless steel tubing will contain the magnets and aluminum caps will constrain them within the sides of the array

- Magnets will be loaded with extreme caution utilizing aluminum fixtures and wooden or aluminum tooling

LEVITATION SYSTEM SAFETY CONSIDERATIONS

- All handling of magnets will be done with gloves and eye protection to ensure manufacturing safety
  - Aprons/body shields and method of securing magnets once out-of-hands required for installation safety
  - In addition, the magnets will always be labeled and will exhibit a warning sign for a high magnetic field
- Before pod fabrication begins, the entire team will be briefed with procedures and warnings for either handling or being in the vicinity of the magnets
- Pod components that come close to the magnets have been designed with non-magnetic material
- Keeping the shop area clean is critical for team safety

MAGNET TRANSPORTATION AND LOADING OBJECTIVES

Transportation of Assembled Halbach Array Units

- Magnet units will be bolted into a shielding unit to allow them to be transported within international regulations for air shipping of magnets
  - 0.00525 gauss 15 feet from the pod
- The shielding unit will also function to hold the Halbach Arrays rigidly in position on the bottom of the pod, allowing easier transportation without suspension deflection
- The shielding unit will also function as the magnet loading mechanism, allowing safe reloading of magnets all the way up to completion day

LEVITATION SYSTEM TESTING

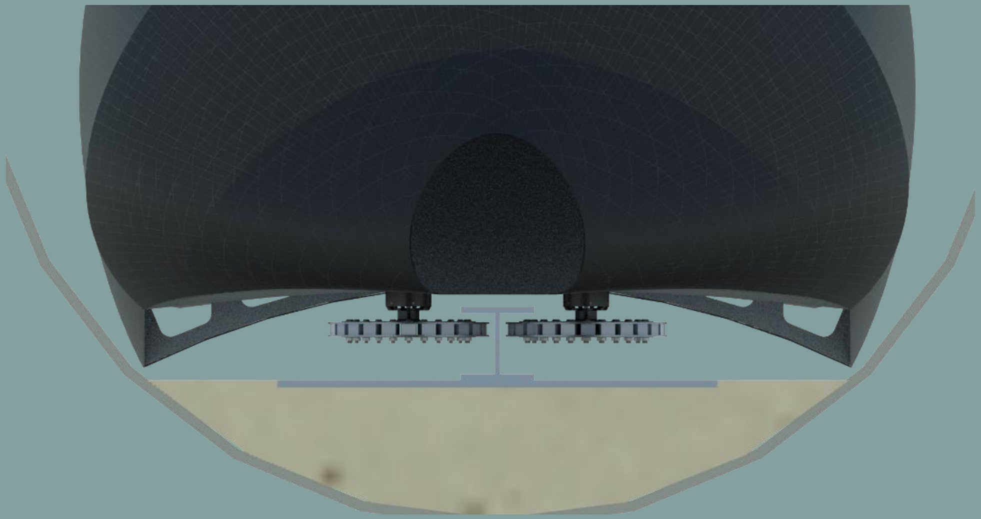
- Suspension system will be tested extensively to find the optimal spring constant and dampening values to mitigate vibrations

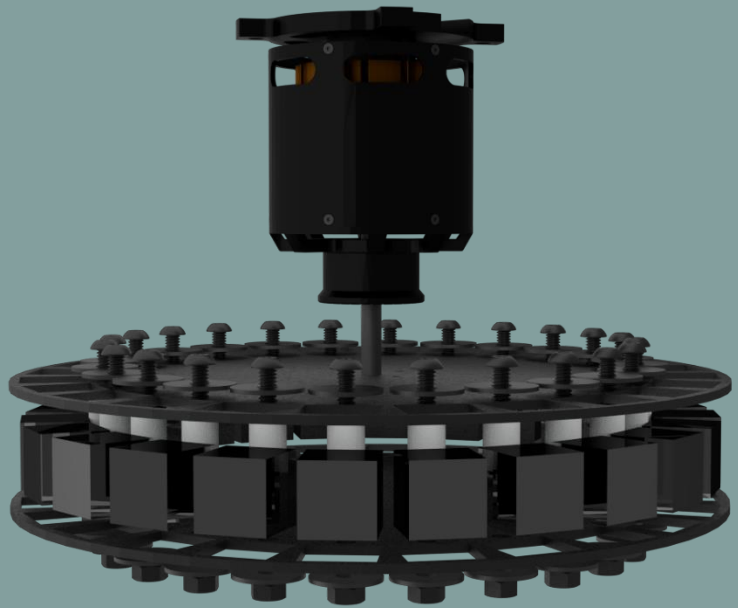
- Measurements of gap height will be made when placing an array over a spinning aluminum at various speeds to match our COMSOL models with empirical data

- Run further FEA and COMSOL simulations to model performance in different scenarios

STABILITY AND FORWARD THRUST SYSTEM

12 Halbach wheels will provide the pod with active stability and additional forward thrust





HALBACH WHEEL SYSTEM MASS

#	Halbach Wheel Stability System	Mass [kg]	Power [Wh]	Cost [$]
288	1" N52 NdFeB Rare Earth magents	35.1	-	$2070.00
12	Turnigy CA80 160kv Brushless Outrunner Motor	18.5	960	$1895.00
12	Hobbywing EZRUN MAX8 V3 150A Brushless Electronic Speed Controller	1.3	-	$1560.00
24	1/8” Waterjet Aluminum Housing Plate	10.5	-	$210.00
-	Misc. Subsystem Hardware	5.9	-	$150.00
TOTAL:		**71.3**	**200**	**$5885.00**

STABILITY AND PROPULSION SYSTEM EXPECTATIONS

Wheels will be stationed in groups of 4 on the pod

All wheels need to produce a combined thrust force of 2000N to counter the drag force experienced by the passive Halbach arrays

Wheels will be modulated to handle a minimum of 167N each

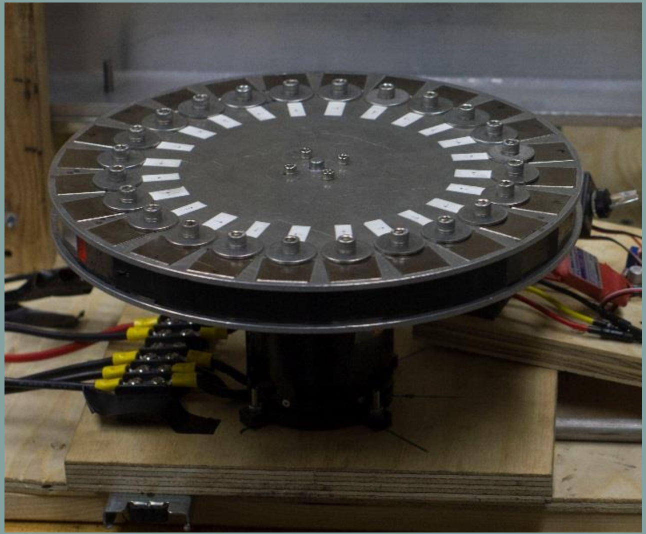
Active lateral, yaw, and pitch stability are provided

Ability to speed up, turn off, and reverse direction is required for various operations

HALBACH WHEEL FUNDAMENTALS

Halbach Wheels provide both stability and propulsion

- Because the wheels have a slip velocity over the forward velocity of the pod, the drag force creates thrust force instead of drag force (as a non-rotating array would)
- Normal forces from Halbach wheels on both sides of the center rail will allow for contactless-centering
- The high stiffness of the gap between the moving magnets and the rail provides large restoring force to lateral disturbances
- Without contact on the center rail, the lifecycle of plates is practically infinite
- Innovative approach that tackles several problems (all forms of stability and counteracting drag) and has not been done before (coupled on a rail)
- This design is easily adjustable with the addition and/or spacing of wheels for countless pod design variations



SUSPENSION AND THRUST SYSTEM BENEFITS

- Counters drag to allow for truly frictionless travel
- Locked on center rail
  - Running at the thrust speed required to counter passive array drag, the restoring force for a lateral disturbance will be 5.5 times as much as the thrust force
- Provides pitch, lateral, yaw stability
- Easy detachment make these wheels very replaceable if damaged
- Permanent magnets and simple design allow for low maintenance
- Coupling on a rail is an innovative approach which provides great stability capabilities

SUSPENSION AND THRUST SYSTEM OPERATION

1. Power up to 50% of operational speed before leaving the pusher
2. Ramp up to operating speed once off the pusher
3. Speed is maintained during run which at a minimum counters the drag force from the passive arrays
4. Increase speed during run for pitch stability control
5. Turn wheels off when approaching the end of the pod
6. Spin in reverse during braking to add redundancy to deceleration
7. Power down at the end of the run

HALBACH WHEEL MANUFACTURING

- Aluminum housing plates to be waterjet cut for optimal precision and finish
- Magnets will be preloaded individually into a loader and a pusher drives the loaded magnet into place in the same way as the passive arrays
- Alignment tools properly position magnets and keep from hitting metal
- These magnets have an extreme amount of force keeping them together when stuck face to face and thus this assembly is prone to pinching fingers and hands and extreme caution is required
- Gloves and safety glasses must be worn at all times and assembly should never occur alone

ASSEMBLY

- Orientation of each magnet is determined for a Halbach array with an outward field (orient poles in a counterclockwise direction as you load magnets in clockwise slots)
- Housing plates are preassembled with spacers, bottom screws/washers, and capped to hold everything in place for magnet loading
- Magnets are loaded one at a time on an adjacent side of loaded magnets and, once in its slot, magnets are capped with a washer and nut
- The final magnet completing the wheel is placed between two already in place and leads to more difficult/dangerous assembly (leakage is eliminated once final magnet in place and amplifies the outer field greatly)
- Prior to loading the final magnet, each bolt and nut are to be tightened

HALBACH WHEEL SAFETY AND TRANSPORT

- Standard safety procedures for the passive arrays will also be used for the Halbach wheels
- Electronic Speed Controllers (ESCs) have a thermal cutoff which will prevent too much power from being drawn and causing further issues
- Protective casings will be developed to secure wheels and protect people near when spinning
- Like the arrays, magnets will need to be contained safely during travel and will be put in spacers placed adequately from potential hazards

HALBACH WHEEL TESTING

- To verify the performance of these wheels, testing individually as well as coupled on an aluminum rail will be conducted for thrust force and dampening response data
- Testing varieties of range from the center beam, an optimal operating distance will be determined
- Testing will be done for ramping the wheel motors up and down to observe voltage and current draws as well as performance in order to optimize operation

POD CONTROL SYSTEM - OVERVIEW

Pod will be controlled by physics-based control system embracing state-of-the-art control strategies

Nonlinear systems require a linearized, operating space model

- "Operating point" refers to a point in the operating space: a particular set of states that define the dynamic properties at that point
- Nonlinear dynamic properties are "linearized" at each point with a first-order Taylor approximation

In our control system, all actuation depends on this operating point

Purpose: to make the pod follow a commanded trajectory

- While the pod trajectory here will be a straight tube, this system is not limited to such a case
- This is achieved by active and/or passive control of 16 pod states: the ordinary 6 degrees of freedom of a free body (spatial and angular) and some of their derivatives and integrals

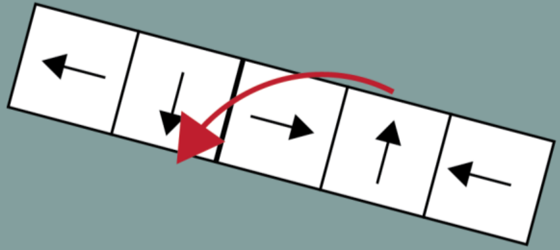
POD CONTROL SYSTEM – PASSIVE STABILITY MECHANISM

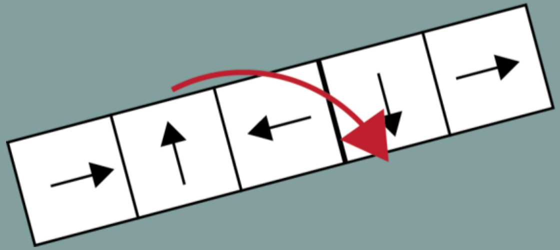
The pod will exhibit some degree of passive stability (depending on operating point) in roll, pitch, yaw, and vertical displacement via the stationary Halbach arrays

This is a form of cross-coupling state feedback: through the stationary Halbach arrays, forward velocity and vertical displacement cause lift and drag forces as well as moments about pitch and roll axes

For a given velocity, the effected lift and drag forces increase in magnitude with reduced vertical displacement (i.e. gap height).

- A disturbance causing rotation about pitch or roll will result in a restoring moment
- A disturbance causing vertical displacement will result in a restoring force





POD CONTROL SYSTEM – ACTIVE CONTROL MECHANISM

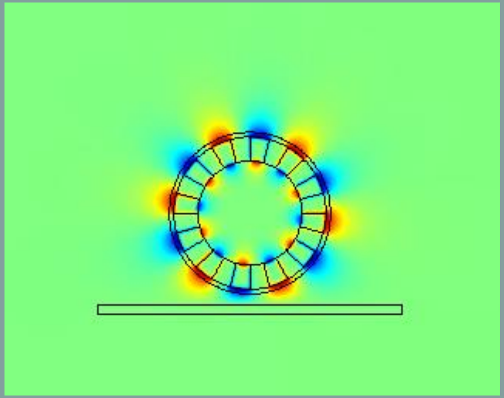
The actuators used for active control are the Halbach wheels

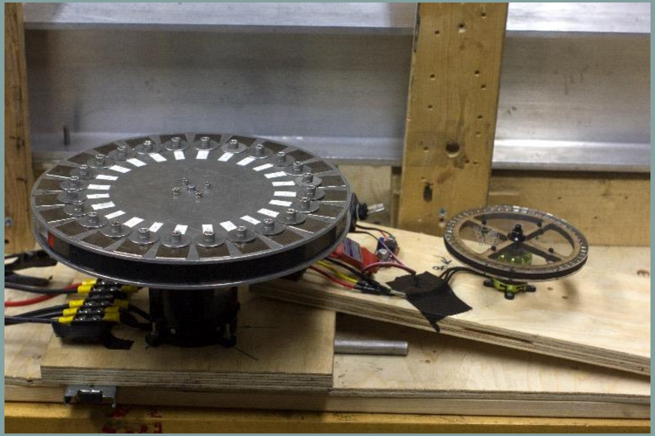
- Produce normal and thrust forces based on rotational velocity of the wheel, pod velocity, and gap height

These are oriented horizontally (i.e. axis of rotation is parallel to global y-axis)

All thrust and normal forces act on the center rail

Results in ability to influence roll, pitch, yaw, and horizontal displacement





POD CONTROL SYSTEM – MANIPULATED INPUT DECOUPLING

Considering that the pod can accommodate up to twelve Halbach wheels, there are effectively twenty-four manipulated input forces

- These inputs are tightly coupled
- None of these inputs are states of interest

For a robust, sensible control system, *manipulated input decoupling* (MID) gives us direct access to states of interest with a high degree of accuracy

As previously stated, the states of interest involve the six degrees of freedom for a free body and some of their derivatives and integrals

- Therefore, to directly influence these, the manipulated inputs must be moments about the three axes of rotation and forces in the three directions of motion

POD CONTROL SYSTEM – MANIPULATED INPUT DECOUPLING

Conceptually, the forces actuated by a Halbach wheel can be represented as a combination of these inputs

Conversely, with certain assumptions and within parameter estimation accuracy, a set of desired inputs can be represented as a set of desired Halbach wheel forces

POD CONTROL SYSTEM – DISTURBANCE INPUT DECOUPLING

The accelerator force is not likely to be aligned perfectly with the center of mass

By integrating a force sensor at the accelerator interface, the amount of disturbance caused by this can be accurately accounted for in the control system

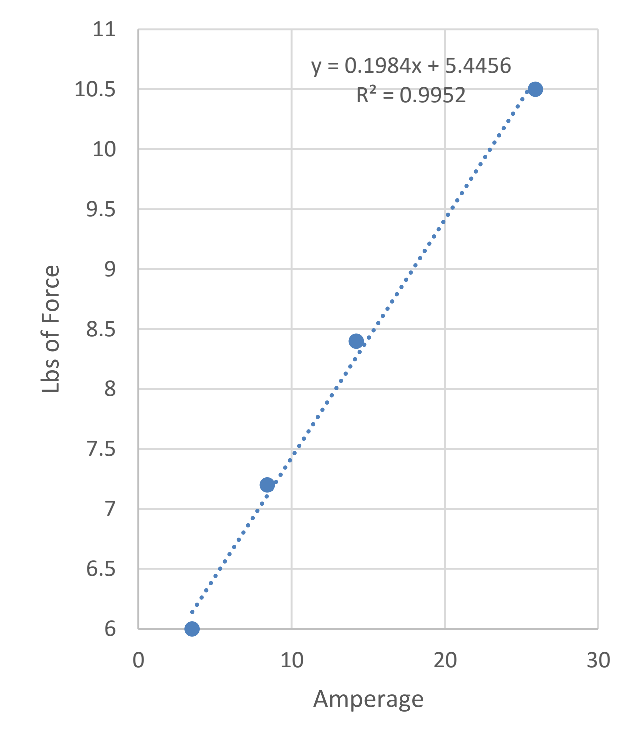
- This is not state feedback and does not come at the expense of other system properties

POD CONTROL SYSTEM – FORCE MODULATION

Empirical data was used to develop relationships between Halbach wheel velocity and produced forces at various operating points

Accurate force modulation is achieved by using developed relationships to determine an angular velocity that will produces the desired forces and using a commercial electronic speed controller to reach and maintain this speed

The forces produced by Halbach wheels are dependent on the operating point of the pod and the rotational velocity of the Halbach wheels



POD CONTROL SYSTEM – CONCEPTUAL BLOCK DIAGRAM

The following block diagram conceptually illustrates the previously discussed strategies

θ refers to an arbitrary angular state

- This diagram only illustrates the various feedback and state manipulations present in the full system

POD CONTROL SYSTEM – CONCEPTUAL BLOCK DIAGRAM

Nomenclature:

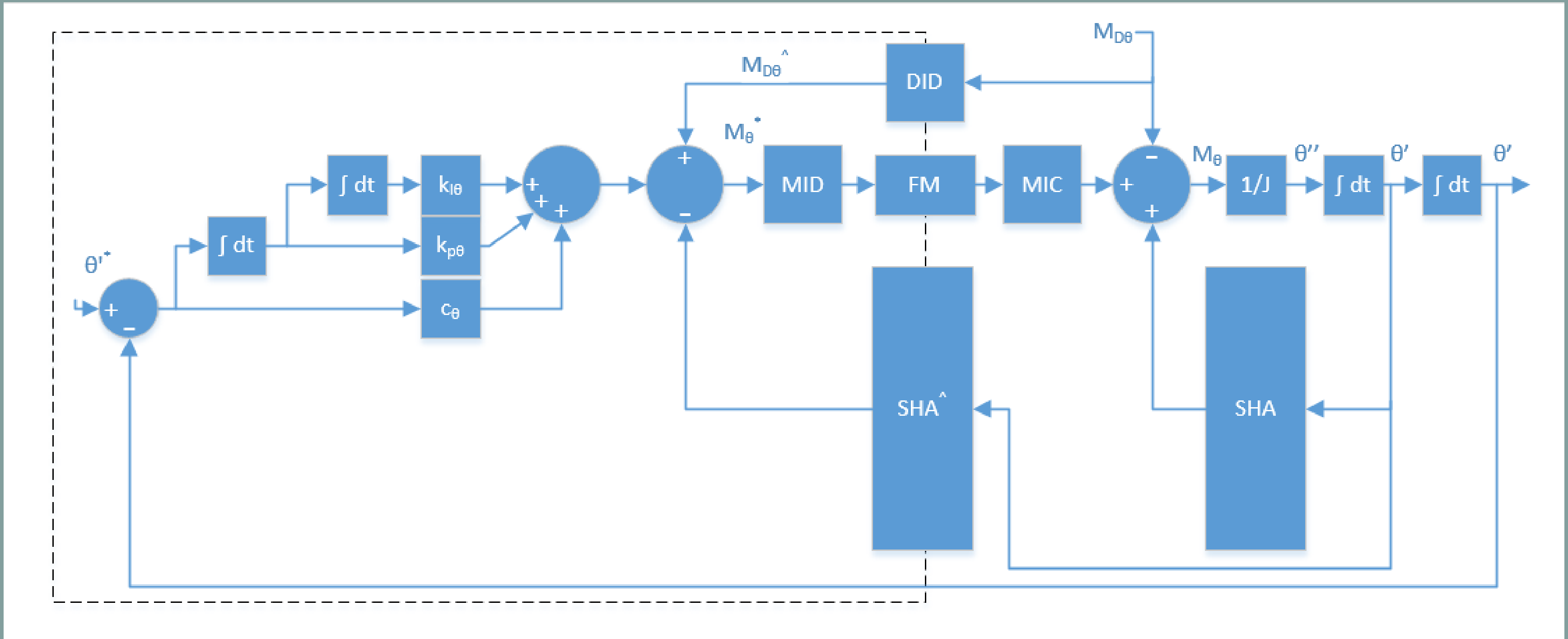
- Items with a superscript "*" are *commanded* quantities
- Items with a superscript "^" are *estimated* quantities
- Items with a subscript "D" are *disturbance* quantities
- Items with no appended script are real quantities
- SHA: Stationary Halbach Array
- DID: Disturbance Input Decoupling
- MID: Manipulated Input Decoupling
- FM: Force Modulation
- MIC: Manipulated Input Coupling
- k,c: State feedback gains
- J: Arbitrary moment of inertia

The contents of the dotted box are in the controller

The contents on the border contain aspects of both

- E.g. processes involving sensors and data processing

POD CONTROL SYSTEM – CONCEPTUAL BLOCK DIAGRAM



See Appendix Section __ for detailed State Diagram

POD CONTROL SYSTEM – SCALABILITY

Additional actuators could also be accommodated

All discussed strategies are entirely scalable

Force modulation would be improved

- Rather than an ordinary COTS non-programmable speed controller, a system would be designed incorporating the fundamental physics of the system in ways that an ordinary speed controller cannot

DID would accommodate the varying center of mass of a commercial pod with varying payloads

ELECTRICAL SYSTEM OVERVIEW

The BadgerLoop Pod uses a Controller Area Network (CAN) to operate the subsystems such that the Modules in the network ensure optimum pod functionality in the event of component or system failure. Some of these main functions are:

- ✓ Data Acquisition
- ✓ Tube Navigation
- ✓ Active Attitude Control
- ✓ 2000N Controlled Propulsion via Halbach Wheels
- ✓ Cabin Monitoring and Safety Alarms
- ✓ Cabin and Battery Fire Protection via Novec 1230 Agent Release
- ✓ Gentle Wheel Bogie Deployment
- ✓ Emergency (Burst) Wheel Bogie Deployment
- ✓ Actively Controlled Regenerative Anti-Lock Braking
- ✓ Plug-in & Wireless Low Speed Propulsion
- ✓ Real-time Deceleration Profile Mapping

OUR CONTROLLER AREA NETWORK - MODULES

BPM = Braking and Propulsion Module

MCM = Magnetic Control Module

VCM = Vehicle Control Module

ECM = Environmental Control Module

WCM = Wireless Connectivity Module

Controller Area Network Functionality

- Modules send all acquired data and status reports to the Wireless Connectivity Module, which gets reported to the Dashboard in real time
- Modules work together to perform system-wide error checking
- If a Module detects that one of its sensors is unusable, it will alert the network, and another Module with the same sensor or same piece of information can provide the data
    - All system-wide data requests contain priority, so if a piece of information from one Module is critical to another, the helping Module can reduce processing power in less critical areas to focus on prioritized system-wide tasks
- If a Module is being overworked, it can hand off data processing to a Module with free processing power via data packets w/ instructions
- All Modules have the ability to set the system into a controlled or emergency braking protocol
- A CAN bus failure prevents communication between the Modules, but they can still function on their own and most Pod functionality would be maintained

OUR CONTROLLER AREA NETWORK

BPM1 & BPM2	MCM	VCM	ECM	WCM
Raises and lowers the Wheel Bogies for braking and low speed auxiliary propulsion	Relies on Pod-Rail and Pod-Track distance sensors to determine Y and Z location in the tube	Uses a combination of tube retroreflective tape detection and accelerometer interpolation to constantly provide an accurate telemetry stream with velocity and position in all 3 axis	Interfaces with a fire suppression system inside both the battery housing and the cabin to alert users of potentially dangerous fires and explosions	Collects all Pod information obtained by the other Modules on the CAN bus and processes/packages the information for the BadgerLoop Dashboard
Changes the flow of power between the motors, Eddy Current brakes, and 24V batteries	Employs a Linearized Operating Space control scheme to command Halbach Wheel spin velocity			
Measures temperature values of various on-board components to ensure a safe braking procedure		Monitors roll, pitch, and yaw with multiple gyroscopic sensing units	Monitors the temperature of the cabin space and other closed off areas inside the pod	Sends packaged information to the BadgerLoop Dashboard via the SpaceX Network Access Panel and our extremely low latency Exis local node
Uses Pulse Width Modulation to provide Regenerative and Eddy Current Anti-Lock Braking	Uses Pulse Width Modulation to control 12 Halbach Wheels to provide the pod with active attitude stability and 2000N of forward force	During acceleration from the SpaceX Pusher, a compression load cell embedded in the accelerator interface analyzes push force and feeds the data to the control system to improve performance by defining initial conditions *(Disturbance Input Decoupling)*		
Monitors the power going into the Eddy Current brakes to ensure a safe and controlled stop			Monitors the temperature of various high-current wires and components to alert the users of a rising threat to prevent escalation	
Utilizes on-board Inertial Measurement Units to analyze deceleration profile and accurately stop at a desired point	Utilizes various externally mounted thermistor clusters to monitor the tube ambient temperature			Readily receives commands from the BadgerLoop Dashboard to control the pod, such as a remote E-stop or a Launch command
Incorporates fail-safe DC Electormagnets to provide a safe braking option in the event of complete power loss	Monitors ambient tube pressure via an absolute pressure gauge	Monitors the door position to confirm that Pod is in a safe state	Monitors the cabin pressure via an absolute pressure gauge	

MODULE CONNECTIONS – BRAKING AND PROPULSION MODULE 1 AND 2

Sensors		Actuators	
x12	**Eddy Brake Magnet Thermistor**	x4	**Motor Power Flow Control** *Electromechanical Relay*
x4	**Disk Brake Shoe Thermocouple**	x1	**Wheel Bogie Linear Actuator** *Reverse Polarity Selector*
x2	**Retroreflective Axle Shaft Encoder**	x1	**Electromechanical Relay Switch** *Solid State Relay*
x4	**Wheel Bogie Limit Switch**	x1	**Wheel Bogie Holding Electromagnet** *Solid State Relay*
x8	**Drum Brake Limit Switch**	x3	**Wheel Bogie Linear Actuator Switch** *Solid State Relay*
x2	**Eddy Brake Magnet Voltage Sensing**	x2	**Eddy Brake Pulse Width Modulation** *Solid State Relay*
x2	**Eddy Brake Magnet Current Sensing**	x2	**Drum Brake Electromagnet Switch** *Solid State Relay*
x1	**Inertial Measurement Unit**		

MODULE CONNECTIONS – MAGNETIC CONTROL MODULE

Sensors		Actuators	
x1	**Ambient Tube Pressure Transducer**	x12	**Halbach Wheels**
x4	**Pod-Track Distance Sensor**		
x6	**Pod-Rail Distance Sensor**		
x9	**Ambient Tube Thermistor**		

MODULE CONNECTIONS – VEHICLE CONTROL MODULE

Sensors	
x3	Inertial Measurement Unit
x2	Door State Limit Switch
x1	Compression Load Cell
x3	Retroreflective Optical Encoder

MODULE CONNECTIONS – ENVIRONMENTAL CONTROL MODULE

Sensors		Actuators	
x18	**Cabin Thermistors**	x1	**Siren/Alarm**
x39	**Wire Thermistors**		
x1	**Cabin Fire Suppression Switch**		
x1	**Battery Fire Suppression Switch**		

DATA ACQUISITION

- In most cases, sensors are grouped in localized “clusters” of 3 units, to maximize both accuracy and redundancy
    1. Module reads in the 3 separate sensor values via I2C or Analog
    2. 3 values are compared to each other
        - If all values are within set difference threshold, the 3 values are averaged and the data value is finalized within the Module
        - If 1 of the 3 sensors is significantly different than the other 2 (faulty), the Module disregards this sensor’s data and proceeds to average the 2 values, which is then finalized within the Module
        - The software on each Module is designed to analyze when and how a sensor fails, and to be able to identify similar sensor failures in real time to differentiate between real and false values in a 2-sensor cluster

- Each Module has a custom Printed Circuit Board built with surface mount component circuitry designed specifically to maximize DAQ performance of that Module’s sensor packages
    - Buffer capacitors for noise filtering
    - Inverting Operational Amplifiers implemented to scale analog input values to peak at 5 volts (SBC44B ADC Input Threshold), to ensure no resolution is lost from the sensor

- Based on the state of each Module and the CAN as a whole, data can be selectively processed to deliver high accuracy in a medium timeframe or medium accuracy in a rapid timeframe
    - Example case: The ECM detects that a specific area of the cabin space is heating up more than the rest, so it reduces sampling frequency & processing power of other thermistors to amp up sampling frequency & processing power for thermistors measuring more critical regions
    - Example case: Pod is in controlled braking procedure, and both BPM1 and BPM2 have faulty accelerometer data, which is needed to stop accurately. The BPMs will send a data request to the VCM, and the VCM will stop taking acceleration/gyroscopic measurements in 3 dimensions, to instead only pull the information critical to the BPMs – in this case, acceleration in the X axis only

DATA ACQUISITION – TUBE NAVIGATION

- The Pod will monitor it's translation down the tube primarily by counting the retroreflective tape strips on the top of the tube and using a set calculation built into the Vehicle Control Module to infer total distance traveled

- Each time a retroreflective strip is detected and processed, it is time-stamped
  - The VCM interpolates velocity in the X axis through position tracking and time-stamp processing

- To provide SpaceX with a constant and <u>accurate</u> telemetry stream of acceleration, velocity, position, and attitude in 3 axis, the VCM constantly measures acceleration and gyroscopic data from a 3-sensor Inertial Measurement Unit cluster
  - The VCM interpolates position and velocity in 3 axis from the IMUs' accelerometers, and streams the telemetry in between retroreflective strip detections

- Because interpolating position and velocity from an accelerometer compounds integration error (thus significantly reducing accuracy over time), every time a retroreflective strip is detected, the integration process resets to the strip-based position and velocity, recognizing that strip as a real and accurate piece of information
  - *This is all in an attempt to reset the interpolation error that gets larger every integration cycle*

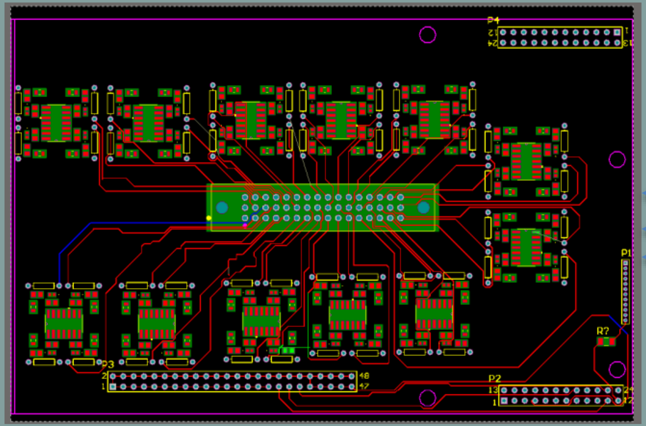
DATA ACQUISITION - TEMPERATURE

- All desired temperature measurements are accomplished with a localized 3-thermistor cluster to improve accuracy and redundancy
- Modules measuring temperature employ a series of Analog Multiplexers to allow many individual thermistors to be analyzed with minimal microcontroller real estate
- Based on the location of each thermistor cluster, heat rise simulations of the Pod dictate the optimum temperature range for desired measurement accuracy – based on these values:
    - Inverting Operational Amplifiers are implemented to properly scale the incoming thermistor voltage to match the 5V analog input on the microcontroller boards
    - A calculated resistor value is chosen to be grounded in a voltage divider circuit to properly center the linearization curve of the specific thermistor model
        - This centering resistor allows Modules to avoid directly implementing the Steinhart-Hart equation and instead utilize an approximation within <2% error

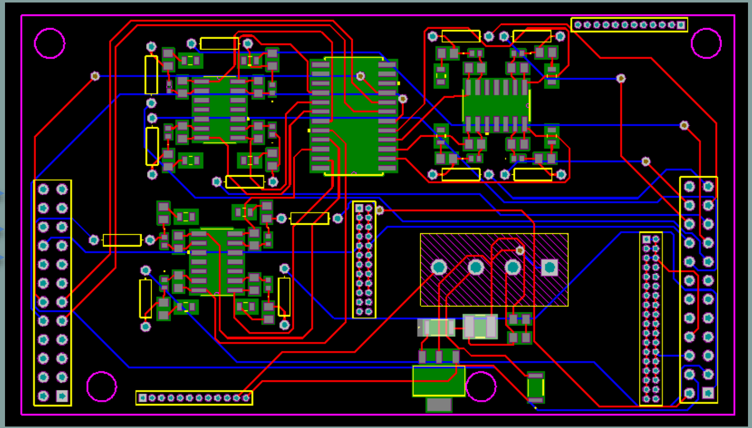
DATA ACQUISITION – CUSTOM PRINTED CIRCUIT BOARDS

- Each Module has a custom Printed Circuit Board on top of its SBC44B Microcontroller
- A combination of ICs, Multiplexers, and RC circuitry allow for each PCB to be customized to optimize the performance of each Modules' DAQ package

PCB Example - ECM



PCB Example - MCM

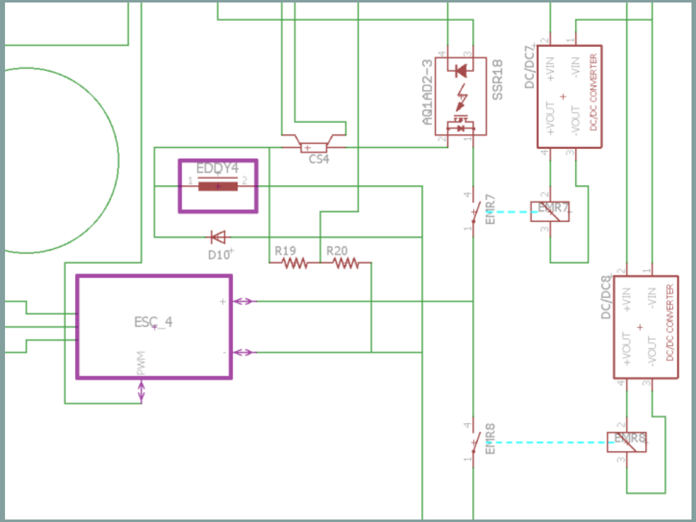


ACTUATION – POWER ROUTING

- The Pod has the ability to switch motor functionality
  - Brake Mode: The motors act as regenerative brakes that also power a secondary Eddy Current brake system
  - Low Speed Auxiliary Propulsion Mode: The motors draw power from the battery to drive forwards or backwards

- To accomplish safely routing 150 amps through various components, the system employs a combination of electromechanical and solid state relays to control where power is allowed to flow in respect to the motor

In the schematic to the right, it is shown how there are 2 electromechanical relays dictating where power can flow through the positive terminal of the Electronic Speed Controller (ESC_4). It is also evident by looking at the schematic that even if the motor or ESC powering the Eddy Current brake were to fail, both relays (EMR_7, EMR_8) could be closed and allow the battery to power the Eddy Current brake in an emergency situation.



ACTUATION – WHEEL BOGIE DEPLOYMENT (FAIL-SAFE)

- The entire braking system is embedded into the CAN such that it is highly controllable but also fail-safe in the event of Braking and Propulsion Module failure or complete Pod power loss

- Fail-Safe braking components
  - Wheel Bogie holding electromagnets
  - Drum Brake activation electromagnets

- If a BPM were to fail or the Pod was to lose power, the following processes would happen
  1. The Wheel Bogie holding electromagnets would lose power, deploying the entire bogie
  2. The Drum Brake activation electromagnets would lose power, springs would push the brake pads into the brake disk, and the pod would go into emergency braking protocol

- In a commanded emergency braking protocol, a linear actuator would also be activated to speed up deployment time

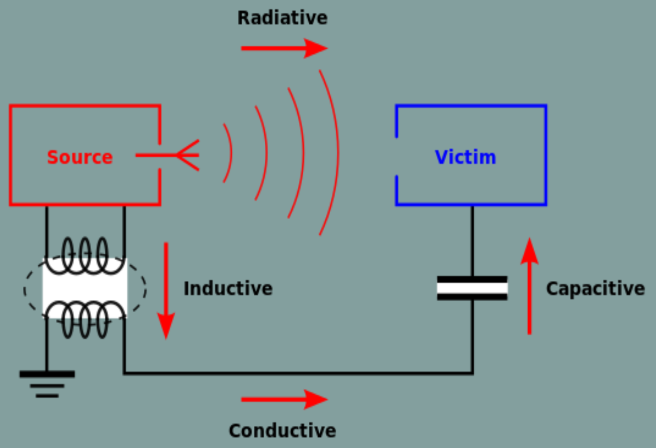
- In the event of Pod failure mid-tube, there are 12V terminals accessible from both the front and back of the Pod for a 12V battery or car jumpstarter to be connected, to release the drum brake electromagnets and allow the Pod to be pushed manually

ELECTROMAGNETIC INTERFERENCE

- Operating environment is innately filled with Electromagnetic Interference (EMI)

- With the addition of 12 spinning Halbach Wheels, EMI is a large concern for DAQ and control systems

- To combat the threats of EMI, many parts of the CAN will have special shielding
  - BPMs, MCM – Both Modules are very close to the Halbach Wheels, and contain critical DAQ and control systems
  - These systems will have extra shielding



ELECTROMAGNETIC INTERFERENCE - SHIELDING

- Three standard options for custom enclosure EMI shielding applications
  1. Conductive Metal
  2. Spray-on Conductive Elastomer Coated Plastic
  3. Conductive 3D-printable Plastic

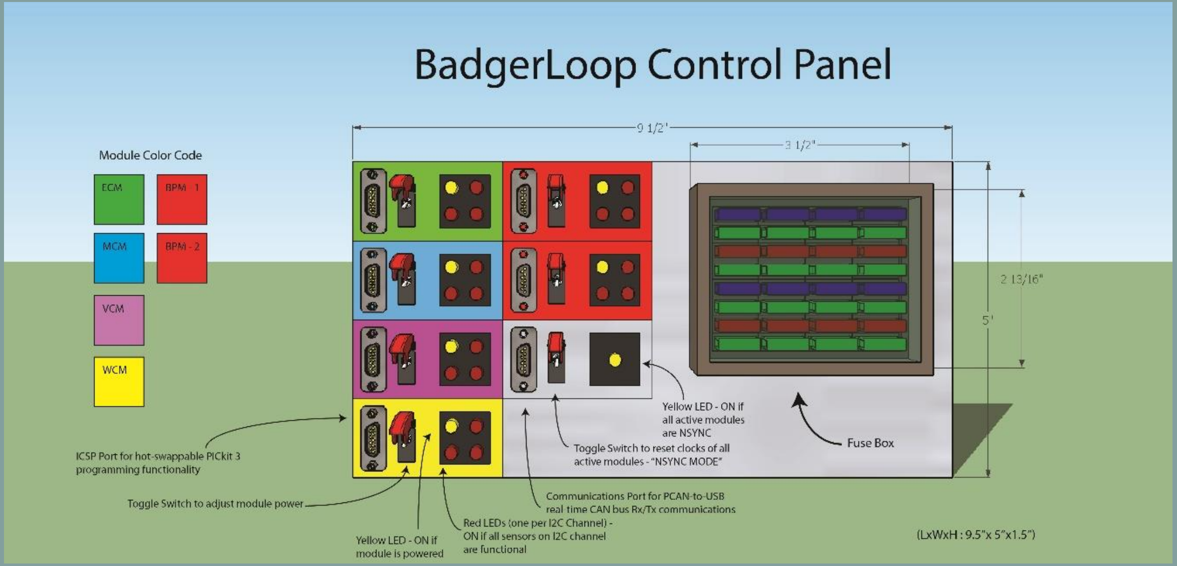
- Conductive 3D-printable Plastic was selected due to cost and versatility

- Once the system is tested under various EMI conditions, susceptible sensors and board circuitry will receive custom 3D printed enclosures

- In addition to sensors and board circuitry, EMI will be shielded at various harnessing points through the application of shielded
  - Sheath cable
  - Conduits
  - Terminals
  - Heat Shrink Tubing

BADGERLOOP CONTROL PANEL

- Control Panel allows for CAN monitoring, simulation, and debugging
- Each Module has a port for In Circuit Serial Programming, and 4 LED indicator lights to show microcontroller and sensor status
- Fusebox contains fuses in series with sensitive or vulnerable components



SYSTEM POWER REQUIREMENTS

- There are 16 Brushless DC Motors on the Pod, each having their own Electronic Speed Controller which receives 24V battery power as well as a Pulse Width Modulation signal
  - 12 Motors are used for the spinning Halbach Wheels
  - 4 Motors are used for regenerative braking and low speed auxiliary propulsion

- Both drive systems will run at 24 Volts DC and will require 100 Amps of constant current / 160 Amps of peak current

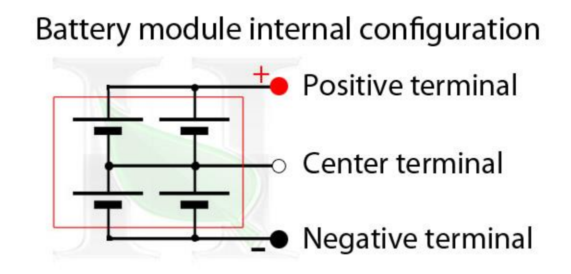
- Because of the unique configuration of this system, traditional EV battery solutions cannot be used
  - Technically one could string all 12 24V Motors in series and use a ~300V EV Pack, but due to the precise control needed for the Halbach Wheels for active stability, this configuration cannot be employed because the back-emf induced by the pod approaching the rail would disturb the line of current flowing between all of the motors

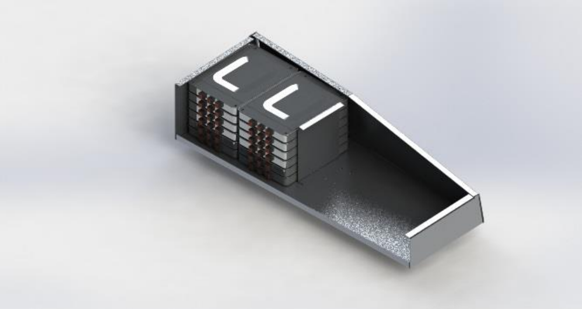
- A 12 Volt pack is needed to power all of the CAN Modules, some sensors, and a few small relays

24V Pack - Estimated Energy Use Per Run [Wh]	12V Packs - Estimated Energy Use Per Run [Wh]
880	76

24 VOLT BATTERY CLUSTER

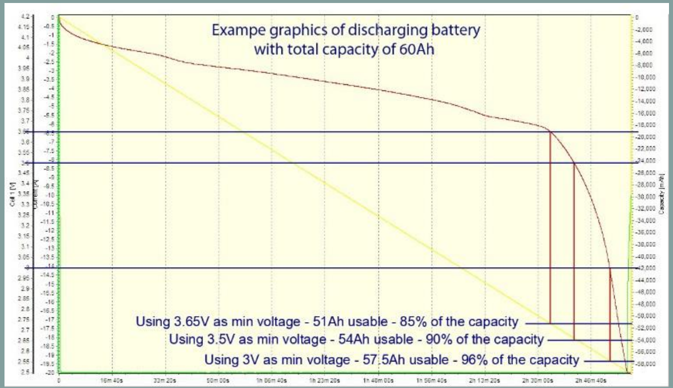
- 7.6v Nissan Leaf battery modules (24 modules total)
  - 2 cells in series, 2 cells in parallel
  - $LiMn_2O_4/LiNiO_2$ cell chemistry
  - Modular nature allows flexibility in power system design
- 3 modules will be placed in series to create 22.8v (nominal) string to be discharged at 240 amps through 2 parallel Electronic Speed Controllers (8 total strings for 16 total Electronic Speed Controllers)
  - Strings are electronically isolated
  - OEM Nissan Leaf bus bars and caps provided by supplier
- Strings are mounted in columns of 2 (6 modules per stack)
- 2 stacks on each side of pod (4 stacks total)
- Stacks will be mounted with supplier provided Nissan Leaf OEM brackets and threaded bolts





24 VOLT BATTERY CLUSTER

- During discharge, current drawn by each Electronic Speed Controller will be 100A continuous / 160A peak
  - 160 amp fuses will be in series with each Electronic Speed Controller
- A PIC microcontroller will be tethered to the onboard battery management system via CAN to perform real time power consumption monitoring
  - Analog measured Voltage Dividers in parallel with each string will be used to monitor voltage
  - Analog measured Current Shunts in series with each string will be used to monitor current
- The microcontroller will use amp-hour integration to perform State of Charge estimation

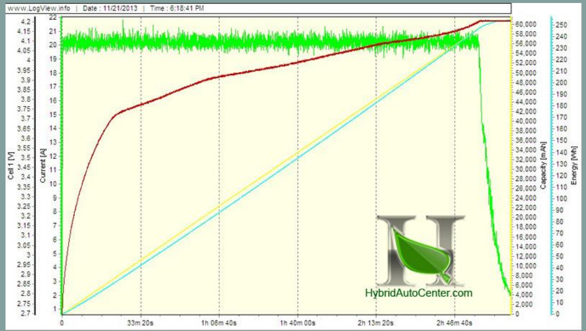


**Discharge curve provided by supplier*

24 VOLT BATTERY CLUSTER

- Strings will be charged independently using KP1200C lithium ion charger
  - 58.4 V max voltage
  - Each string's terminals will be wired to a charging receptacle (1 receptacle per string)
  - The charging panel will be situated on the front of one of the battery boxes

- One Orion BMS JUNIOR to balance and monitor string charging
  - Strings are balanced in referenced to previously charged string to ensure equal voltage across packs
  - After a string is fully charged, the BMS JUNIOR cuts off charging via CAN-enabled charger
    - 8 position rotary switch changes cell voltage balancing pins from string to string
  - The charger is manually moved to the next string receptacle



**Charge curve provided by supplier*

POWER SYSTEM – LOW VOLTAGE SYSTEMS BATTERY PACK

- 12v, 20 Ah Stark Power 'Ultra Energy' LiFePO4 Energy Storage Pack – will be used for all CAN hardware and some sensors
  - Internal battery management system allows simplified integration
  - 30 amp max discharge current

- Will be charged with 12v 20A LiFePO4 "smart" charger from Stark Power
  - Has build in voltage shutoff

Image taken from Stark Powers website

POWER SYSTEM – FABRICATION AND MAINTENANCE SAFETY

- Each string is independent, limiting high voltage hazards
- Even though packs will never be strung for high voltage, precautions for handling high voltage systems will be followed
  - All team members will be briefed on handling modules
  - Only designated team members will have access
    - Battery lockouts will be implemented
- High voltage and current warning labels will indicate dangerous areas
- Plastic tools will be used for terminal and busbar handling
- *WEMPEC and Johnson Controls Lab on campus for safety overview and confirmation*

IMPLEMENTATION OF CONTROLLER AREA NETWORK (CAN)

- Various modules in the pod will be communicating using the CAN 2.0B protocol in accordance with ISO 11898 standard.
- CANOpenNode enables us to conform to ISO 11898 standard and CANOpen standard.
- Each module has an EDS file, enabling our CANOpen network to pass the CiA CANopen conformance test.
- The software stack used for inter-module communication is an open-source software stack known as CANOpenNode.

CANOPEN STANDARD

- The communication model used for our CAN network is push-based producer/consumer.
- Each module has a unique node identifier, allowing other nodes to distinguish where each CAN message originated from
- Each node will be simultaneously be a producer and consumer; there are many instances where data must be sent from one node to another and vice versa.
- Being a push-based producer/consumer CAN network model, each node will be broadcasting messages as a Process Data Object (PDO)

PROCESS DATA OBJECT (PDO)

- CAN Messages that contain process data (sensor values, node status, etc) are called Process Data Objects (PDOs)
- Each PDO and its content can be interpreter by the consumer (receiving node) by its CAN Object Identifier (COB-ID)
- In accordance with CiA standards, each node will have an object dictionary that will contain the PDO Mapping
- The PDO Mapping describes which individual process variables are packaged, how they are arranged, the data type of each process variable, and the length of each

PROCESS DATA OBJECT (PDO) (CONT.)

- Currently, all PDOs transmitted are of the asynchronous type
- Asynchronous PDOs are event-controlled. This means that each PDO will be transmitted immediately after an event occurs
- An event can be a node status change, sensor data reading, or any change in node behavior

PDO MAPPING AND EDS FILES

- The PDO Mapping for our CAN network can be found in the EDS file for each node
- The EDS file for each node will contain an object dictionary, which will allow each CAN node to readily interpret any CAN message broadcast on the CAN network
- EDS Files are required for each node/module to pass the CiA CANopen conformance test

CIA CANOPEN CONFORMANCE

- Each of our modules will pass the CAN in Automation CANOpen conformance test
  - The test is designed to verify that CANopen devices are compliant to CiA 301 version 4.2
  - The test verifies that devices are compliant to the CANOpen application layer
- The CANOpen conformance test tool:
  - Tests the EDS file associated with a CANOpen device against the object dictionary of the CANOpen device
  - Verifies the CANOpen application layer and its services

SENSOR DATA ACQUISITION

- All sensors and external hardware will be connected to the GPIO PINs on each microcontroller
- Our PIC18F458 microcontrollers feature a total of 39 GPIO PINs of which 15 can be used for analog to digital conversion (ADC) and 6 of which are used for CAN networking and I2C
- Analog to digital conversion enables the connection of variable voltage analog sensors to the microcontrollers
- The data is then read and returned as a 4 byte unsigned integer

SENSOR DATA ACQUISITION SOFTWARE IMPLEMENTATION

- The various have various sensor readings than must be transmitted over the CAN network for other modules
- The sensor data is provided over several different data transmission protocols
  - Digital (I2C, digital GPIO logic high/low)
  - Analog (through Analog to Digital conversion (ADC) on modules)
- I2C sensors will be operating on the I2C bus at 400kHz
- Digital GPIO logic high/low can be read directly by each module with a single line of C code
- ADC requires the use of C interrupts and switching between ADC channels as data becomes available.

ANALOG TO DIGITAL CONVERSION (ADC)

- All modules will have at least one analog sensor connected to a GPIO pin set for ADC
- The PIC18F458 microcontrollers complier libraries contain C code that enables the reading of ADC values in a single line of C code
- Through these libraries we are able to seamslessly capture analog inputs just as we are digital GPIO inputs

ANALOG TO DIGITAL CONVERSION (ADC) SOFTWARE IMPLEMENTATION

- All modules will have at least one analog sensor connected to a GPIO pin capable of ADC
- ADC computation requires a few clock cycles to complete
- C interrupts are used to halt current code instruction and retrieve/store the ADC value from each channel (analog pin)
- Each microcontroller is able to seamlessly gather I2C and ADC data simultaneously

BRAKING AND PROPULSION MODULE 1 AND 2 - SENSORS

- 4 Thermistor clusters each with 3 thermistors
  - Data will be gathered via ADC (4 bytes)
  - For each cluster, the 3 values will be checked for errors/outliers
  - If acquisition was error free, the values will be averaged to a single 4 byte value
  - Thus, all thermistor cluster values are stored in a total of 16 bytes
- 4 Thermocouples
  - Data will be gather via ADC (4 bytes)
  - Thus, all thermocouple values are stored in a total of 16 bytes

BRAKING AND PROPULSION MODULE 1 AND 2 - SENSORS (CONT.)

- 2 Retroreflective shaft encoders
  - Data will be gathered via ADC (4 bytes)
  - Thus, all retroreflective shaft encoder values are stored in a total of 8 bytes
- 12 Limit Switches
  - Each one needs 1 bit and will connected to a GPIO pin
  - 12 bits => 3 bytes
  - Thus, all limit switch state values are stored in a total of 3 bytes
- 4 Potentiometers
  - Data will be gathered via ADC (4 bytes)
  - Thus, all potentiometer values are stored in a total of 16 bytes

BRAKING AND PROPULSION MODULE 1 AND 2 - SENSORS (CONT.)

- 1 Accelerometer
  - Only x-axis values need to be transmitted over the CAN network
  - Each accelerometer values (x,y,z) is returned as a signed 16 bit integer over I2C
  - 16 bits => 2 bytes
  - Thus, since only the x-value is needed, the accelerometer value is stored as a total of 2 bytes
- 4 Shunt breakouts
  - Data will be gathered via ADC (4 bytes)
  - Thus, all shunt breakout values are stored in a total of 16 bytes

MODULE SENSOR LIST – BRAKING AND PROPULSION MODULE 1 AND 2

Sensors		Data Acquisition Type	Number of bytes needed for data
x12	Thermistor (groups of 3)	ADC	4 bytes per group; 16 bytes total
x4	Thermocouple	ADC	4 bytes per thermocouple; 16 bytes total
x2	Retroreflective shaft encoder	ADC	4 bytes per encoder; 8 bytes total
x12	Limit switch	Digital GPIO	1 bit per switch; 1.5 bytes total
x4	Potentiometers	ADC	4 bytes per potentiometer; 16 bytes total
x1	Accelerometer (only x-axis)	I2C	2 bytes per axis; 2 bytes total
x4	Shunt breakout	ADC	4 bytes per breakout; 16 bytes total
Total	---	---	78.5 bytes total

MAGNETIC CONTROL MODULE – SENSORS

- 1 Pressure sensor
  - Data will be gathered via ADC (4 bytes)
  - Thus, all pressure values are stored in a total of 8 bytes
- 5 Proximity Sensors
  - Each proximity value is returned as a signed 16 bit integer over I2C
  - 16 bits => 2 bytes
  - Thus, all proximity values are stored in a total of 10 bytes
- 5 Thermistor clusters each with 3 thermistors
  - Data will be gathered via ADC (4 bytes)
  - For each cluster, the 3 values will be checked for errors/outliers
  - If acquisition was error free, the values will be averaged to a single 4 byte value
  - Thus, all thermistor cluster values are stored in a total of 20 bytes

MODULE SENSOR LIST – MAGNETIC CONTROL MODULE

Sensors		Data Acquisition Type	Number of bytes needed for data
x1	Pressure sensor	ADC	4 bytes per sensor; 4 bytes total
x10	Proximity sensor	I2C	4 bytes per value; 40 bytes total
x16	Thermistor (groups of 3)	ADC	4 bytes per group; 20 bytes total
Total	---	---	64 bytes total

VEHICLE CONTROL MODULE – SENSORS

- 3 Accelerometer/Gyroscope
  - Each accelerometer value (x,y,z) is returned as a signed 16 bit integer over I2C
  - Each gyro value (x,y,z) is returned as a signed 16 bit integer over I2C
  - 16 bits => 2 bytes
  - Thus, all accelerometer/gyroscope values are stored in a total of 36 bytes
- 2 Limit Switches
  - Each one needs 1 bit and will connected to a GPIO pin
  - 2 bits => 0.25 bytes
  - Thus, all limit switch state values are stored in a total of 0.25 bytes
- 2 Retroreflective shaft encoders
  - Data will be gathered via ADC (4 bytes)
  - Thus, all retroreflective sensor values are stored in a total of 8 bytes

MODULE SENSOR LIST– VEHICLE CONTROL MODULE

Sensors		Data Acquisition Type	Number of bytes needed for data
x3	Accelerometer (accel – x,y,z-axis; gyro – x,y,z-axis)	I2C	2 bytes per value; 36 bytes total
x2	Limit switch	Digital GPIO	1 bit per switch; 0.25
x3	Retroreflective sensor	Digital GPIO	4 bytes per sensor; 12 bytes total
x1	Compression Load Cell	ADC	4 bytes per sensor; 4 bytes total
Total	---	---	52.25 bytes total

Environmental Control Module - Sensors

- 2 Pressure Switches
  - Each proximity value is returned as a signed 16 bit integer over I2C
  - 16 bits => 2 bytes
  - Thus, all proximity values are stored in a total of 10 bytes
- 1 Pressure sensor
  - Data will be gathered via ADC (4 bytes)
  - Thus, all pressure values are stored in a total of 4 bytes
- 19 Thermistor clusters each with 3 thermistors
  - Data will be gathered via ADC (4 bytes)
  - For each cluster, the 3 values will be checked for errors/outliers
  - If acquisition was error free, the values will be averaged to a single 4 byte value
  - Thus, all thermistor cluster values are stored in a total of 76 bytes

MODULE SENSOR LIST – ENVIRONMENTAL CONTROL MODULE

Sensors		Data Acquisition Type	Number of bytes needed for data
x2	Pressure switch	Digital GPIO	1 bit per switch; 2 bits total
x1	Pressure sensor	ADC	4 bytes per value; 4 bytes total
x45	Thermistor (groups of 3)	ADC	4 bytes per group; 180 bytes total
Total	---	---	184.25 bytes total

DATA TRANSMISSION TO BASE - EXIS

In order to transfer data from our pod to the main station we use a system called Exis

Exis allows us to transfer data from our onboard sensors such as:

- Temperature
- Gyroscope/Accelerometer
- Proximity
- Important Admin Control
- And several other vital messages

DATA TRANSMISSION TO BASE - EXIS

All of our data must be transferred at a very high rate in order to ensure the safety and success of our pod and Exis makes this possible for us

Exis allows us to group sensors by type such that new data values are published to their specific endpoint

Our dashboard subscribes to each of the sensor endpoints, thus whenever a new piece of data is published - our dashboard will be notified and will update our team at the base station as need be

DATA TRANSMISSION TO BASE - EXIS

In order to ensure the security of our pod and the data we are transferring, we are able to set up a local Exis Node at the base station so we do not need to transfer any information "over the air"

This will safeguard our data and lower latency between our Network Access Panel and our local machine

All data transmission will be completely secured over the same encryption used for HTTPS with Exis

DATA TRANSMISSION TO POD - EXIS

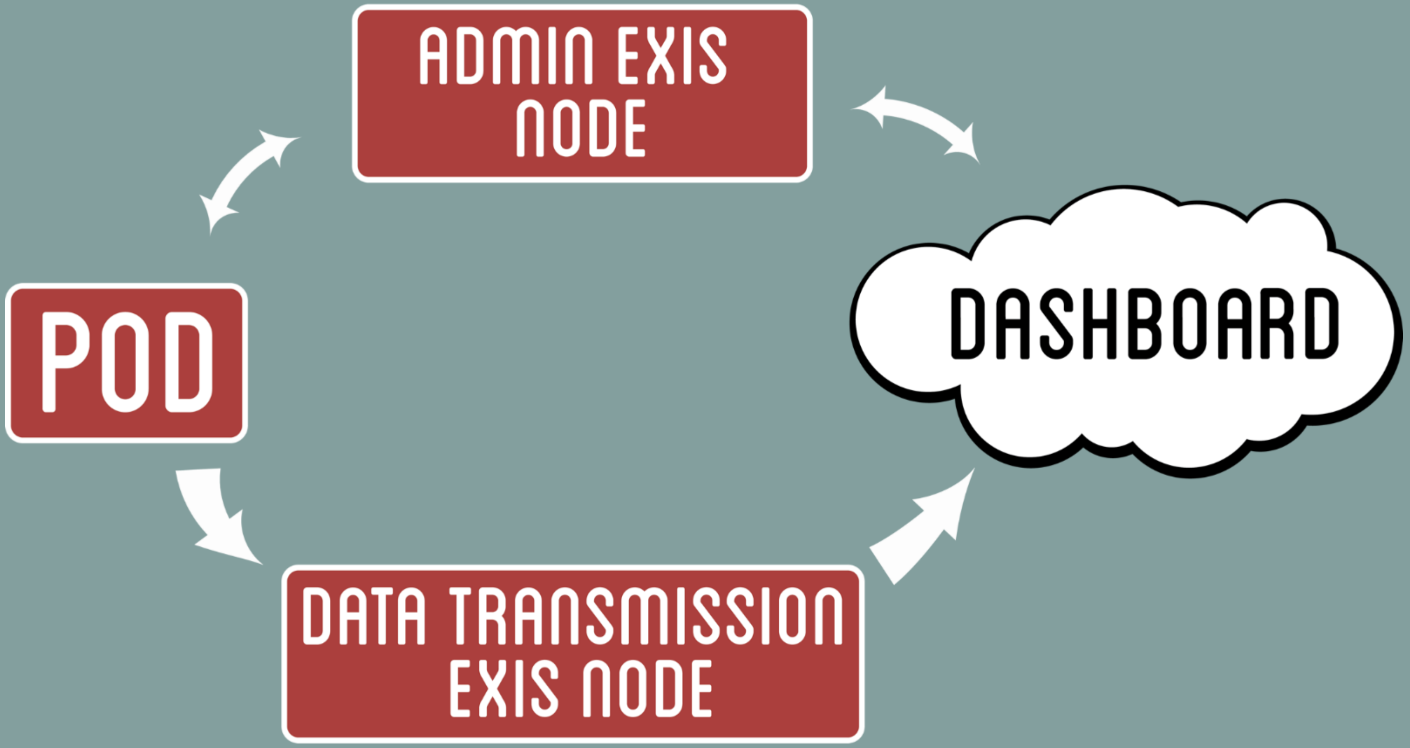
- There may be certain situations in which we must communicate with the pod from base station such as an emergency braking command
- We will have a separate Exis Node set up purely to deal with admin communication. We feel that we do not want any data clogging this Node other than emergency and extremely important messages
- Our Wireless Communication Module will be listening to these Administrative endpoints and will react accordingly to the messages that are published

DATA TRANSMISSION TO POD - EXIS

Some of the administrative commands would include:

- Emergency Braking Command
- Startup Command
- Low Speed Propulsion Command

DIAGRAM OF DATA TRANSMISSION - EXIS



DATA TRANSMISSION – EXIS

- The previous slide's diagram depicts how are communication works
- Pod will publish the data gathered by the onboard sensors to either of the 2 nodes, depending on the type of data
- Dashboard subscribed to that specific endpoint on the Node, which will be fired when something is published on that specific endpoint
- Nodes are the middle-man of message communication for our system

TEST DATA – EXIS

- Publish and subscribe call (used to communicate to and from pod) testing:
  - 9,500 publishes were made in a row
  - Time taken to receive publishes from subscriber:
    - 15ms avg.
    - 2.6ms min.
    - 67ms max

DISPLAYING AND ANALYZING DATA – BLDASHBOARD

This is a rendering of the BadgerLoop Dashboard. It will represent all vital data that is being transmitted from the pod to us. It will also give us the ability to transmit messages back to the Pod.

DISPLAYING AND ANALYZING DATA - BLDASHBOARD

- Each progress gauge will represent data that is transmitted to us from the Wireless Communication Module
- The BLDashboard allows each iPad it is loaded onto to see the same data simultaneously
- Each team will be able to have a live progress update of our system through this dashboard

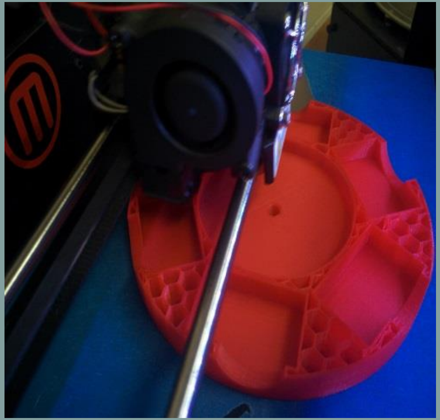
VIRTUAL REALITY AND BADGERLOOP

- UX Issues:
  - Early pod testing is dangerous for human passengers but they want to know what it feels like to ride within the pod
  - If windowless rooms are not enjoyable, windowless pods are likely not enjoyable either
- VR Solutions:
  - Use pod orientation/translation to simulate a remote ride for the user
  - Provide drop down VR headset for passengers in windowless pods with scenery/entertainment

VIRTUAL REALITY CAMERA SYSTEM

- Captures surrounding scenery in 360 degree views and algorithm stitches input video streams for retroactive stereoscopic 3D VR video playback
- Easily scalable prototype, transportable by drone or ground vehicle in order to capture surrounding environment

VR Camera Prototype



3D printed VR mount

Intermediate Video Stitching Result

VIRTUAL REALITY VIEWING & DISTRIBUTION

Create virtual outdoor scenes which map to pod path completion

Target Viewing Devices:

- Oculus Rift
- Mobile Devices

Initial VR scenes will be entirely computer generated and later incorporate real outdoor environments

New York Subway equirectangular projection

VIRTUAL REALITY – ADDITIONAL CONCEPTS

Develop passenger VR UI overlays to display basic information like transit times, food menus, etc.

Model final pod interior to intergrade captured outdoor environment for VR headset display

STORED ENERGY

Stored Energy			
#	Description	Energy Amount	Energy Type
1	12 [V] $LiFePO_4$ Battery Pack	864 kJ	Electrochemical
2	24 [V] $LiMn_2O_4/LiNiO_2$ Battery Pack	38,742 kJ	Electrochemical
4	Novec 1230 Fire Suppression Agent Pressure Vessels	240 psi	Pressure Vessel

HAZARDOUS MATERIALS

Hazardous Materials			
#	Description	Amount	Hazardous Comments
862	1 [in] Neodymium Magnets (Levitation System and Halbach Wheels)	105.5 [kg]	Large amounts of magnets pose safety concern as metal objects nearby can be severely attracted to the magnets, and may cause issues with individuals with pacemakers
1	12 [V] $LiFePO_4$ Battery Pack	3.0 [kg] 864 kJ	Small lead acid replacement car battery. Very safe chemistry with internal BMS.
2	24 [V] $LiMn_2O_4/LiNiO_2$ Battery Pack	88.8 [kg] 38,742 kJ	Modules in isolated strings of 3 for 22.8V strings. Each module supplies two parallel ECS's and motors. Discharging at nominal current for much less than spec time.
1	Novec 1230 Fire Suppression Agent	9.5 [kg]	Inhalation of vapors, mist, and spray may result in health issues. Byproducts of thermal decomposition are also toxic. See Novec 1230 MSDS in the appendix.
1	Carbon Fiber Shell	N/A	Machining carbon fiber can produce carcinogenic materials that can be a health hazard to those manufacturing.

VACUUM COMPATIBILITY

Vacuum Compatibility Issues		
#	Description	Mitigation Action
24	Spring damper suspension shocks	The shocks will be filled with a vacuum compatible oil
12	Halbach Wheel Motors have bearings packed with grease	The bearings will be packed with a vacuum compatible grease
16	Nylon Roller Wheels having bearings packed with grease	The bearings will be packed with a vacuum compatible grease
7	Retro-reflective sensor within encased housing	Testing in vacuum environment will be conducted to validate if the sensor housing will hold up in low pressure environments. If it fails a small hole will be drilled in the transparent window to allow pressure differential to equalize.
10	Proximity sensor within encased housing	
2	Pressure sensor within encased housing	

FIRE PROTECTION SYSTEM – POD INTERIOR

- Indirect clean agent total flood system using Novec 1230
- Flexible detection tubing is spread throughout high-hazard areas
- Once a fire has been detected, suppression agent is directed through rigid piping to nozzles at either end of the pod
- 10 second depletion of first 7lb agent tank for initial knockdown (meets NFPA 2001)
- 10 minute depletion of second 7lb agent tank to keep fire suppressed (meets NFPA 2001)

(courtesy of SEVO Fire Protection Systems and United States Alliance Fire Protection Inc.)

FIRE PROTECTION SYSTEM – BATTERY HOUSING

- Direct clean agent total flood system using Novec 1230
- Flexible tubing acts as both detection tubing and suppression agent pipe
- Agent is stored at pressure (240 psi) throughout entire pipe system at all times
  - When fire burns through flexible tubing (248*F), a nozzle is formed and suppression agent is applied directly to the seat of the fire
- Rapid actuation and extremely reliable

(courtesy of SEVO Fire Protection Systems and United States Alliance Fire Protection Inc.)

3M NOVEC 1230 FIRE SUPPRESSION AGENT

- Non-ozone depleting characteristics
- Low heat of vaporization and high vapor pressure
  - Rapid transformation from liquid to gas = rapid extinguishment with no leftover residue (evaporates in seconds when poured on surface)
- Liquid at room temperature
  - Can transfer using conventional pumping/pouring methods
- Works to absorb heat – does not chemically interrupt the combustion process like other agents
- Near zero electrical conductivity
- Relatively non-toxic to humans (see exposure guidelines in appendix)

(courtesy of SEVO Fire Protection Systems and United States Alliance Fire Protection Inc.)

FIRE PROTECTION SYSTEM – SUMMARY

#	Fire Protection System	Mass [kg]	Cost [$]
1	Novec 1230 Suppression Agent	9.2	-
2	7lb Capacity Tank with Valve Assembly, Mounting Brackets, and Fittings	7	-
2	3lb Capacity Tank with Valve Assembly, Mounting Brackets, and Fittings	3	-
-	6mm dia. 248*F Pneumatic Detection/Suppression Tubing	1.4	-
-	3/8” Suppression Agent Pipe	2.25	-
1	Misc. Tees, Plugs, Grommets, Pipe Fittings, Nozzles, Clamps, Valves, Gauges	6.9	-
TOTAL:		**29.75**	**$7825.40**

FAILURE MODE AND EFFECTS ANALYSIS

- Color coded by system & Ordered by Risk Priority Number

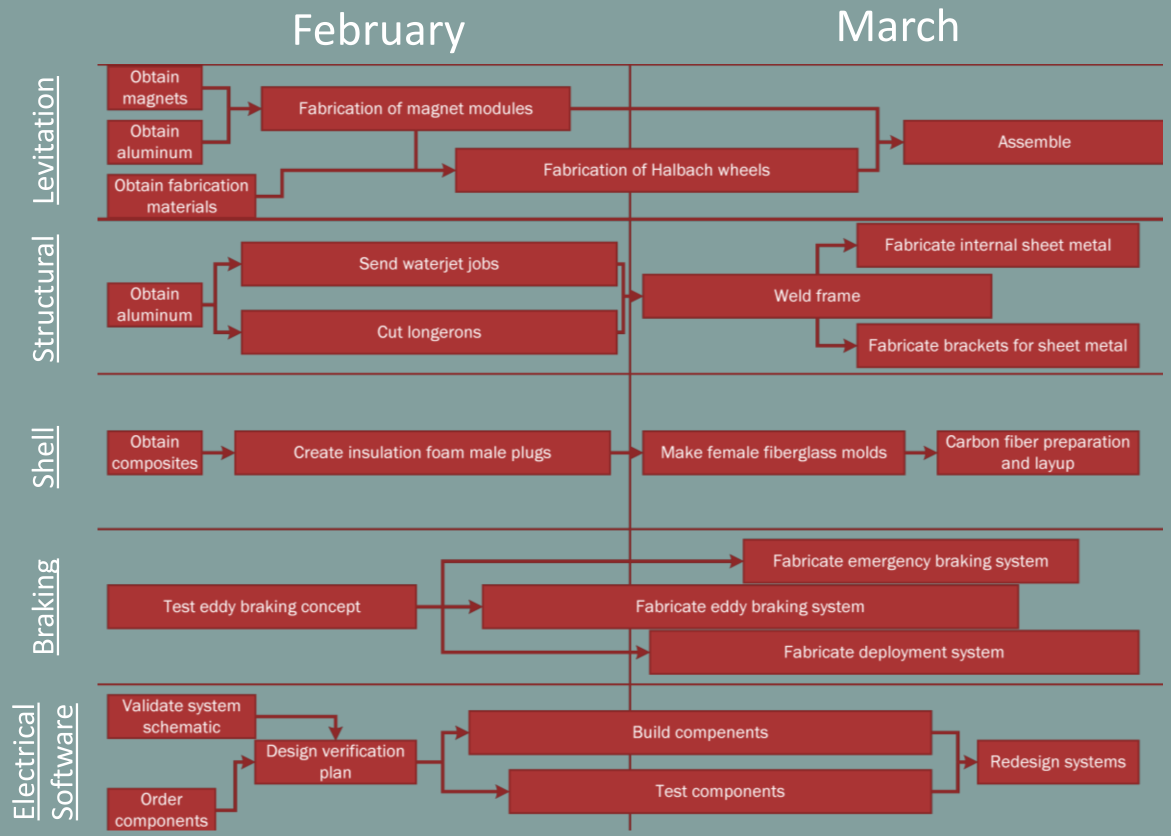
System	Component Function or Process	Failure /Emergency Event	Potential Impact	Potential Causes	Detection	Severity Rating	Occurrence Rating	Detection Rating	Risk Priority Number
Levitation System	Passive Halbach Array Magnet Function: Enables p	Magnets Interact with Debris/Other Halbach Array Magnets	Magnets may attract	Loose components on po	None - only visual/auditory i	6	8	10	480
Stability System	Halbach Wheel Function (Active Stability): Enables	Magnets Interact with Debris/Other Halbach Array Magnets	Magnets may attract	Loose components on po	None - only visual/auditory i	6	8	9	432
Structural System	Underbody Frame/Bogie Function: Allows wheel a	Deformation of Any or All Structural Members in the Underbody	Deformation of under	Manufacturer/fabrication	None - only visual/auditory.	10	4	9	360
Service Propulsion/Wheel Assembly System	Service Propulsion Motor Function (note - same mo	Excessive Load on Motor (any axle combination)	Premature wear and t	Other motor failures, exc	Voltage and current will be r	5	8	8	320
Fire Protection System - Battery Housing	Suppression Tank Function: To provide a total floo	Tank Overpressure - Severe	In extreme cases, tanl	Manufacturer defect or ta	Gauge on tank valve - no ele	10	3	9	270
Structural System	Underbody Frame/Bogie Function: Allows wheel a	Failure of Any or All Structural Members in the Underbody	Failure of any part of	Manufacturer/fabrication	None - only visual/auditory.	10	3	9	270
Service Propulsion/Wheel Assembly System	Wheel Function: Allows the pod to move when it is	Debris Kicked up by Tire	Debris may be sent at	Debris caught in tire, pod	None - only visual/auditory i	4	6	10	240
Levitation System	Passive Halbach Array Suspension Function: Allows	Suspension Assembly Structural Deformation (any component)	Linear Halbach array r	Manufacturer/fabrication	None - only visual/auditory i	7	3	10	210
Stability System	Halbach Wheel Function (Active Stability): Enables	Excessive Load on Halbach Wheel Motor (any axle combination)	Premature wear and t	Close proximity to repulsi	Thermistors monitoring tem	3	8	8	192
Structural System	Rib, Longeron, and Stringer Function: Provides the	Rib Deformation	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	7	3	9	189
Structural System	Rib, Longeron, and Stringer Function: Provides the	Stringer Deformation	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	7	3	9	189
Structural System	Rib, Longeron, and Stringer Function: Provides the	Longeron Deformation	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	7	3	9	189
Emergency Braking System - Self Energizing D	Brake Shoe Function: Allows energy transfer to occ	Brake Shoe Structural Failure (any axle combination)	Depending on axle co	Manufacturer/fabrication	Indirect detection via pod ac	9	2	10	180
Levitation System	Passive Halbach Array Magnet Function: Enables p	Various Metal Components Separate from Linear Halbach Array Assembly	Metal components wi	Manufacturer/fabrication	None - only visual/auditory i	6	3	10	180
Levitation System	Passive Halbach Array Magnet Function: Enables p	Linear Halbach Array Complete Structural Failure	Magnets/linear Halba	Manufacturer/fabrication	None - only visual/auditory i	9	2	10	180
Levitation System	Passive Halbach Array Suspension Function: Allows	Suspension Assembly Structural Failure (any component)	Linear Halbach array r	Manufacturer/fabrication	None - only visual/auditory i	9	2	10	180
Stability System	Halbach Wheel Function (Active Stability): Enables	Magnets Separate from Halbach Wheel (any combination)	Magnets will be eject	Manufacturer/fabrication	None - only visual/auditory i	6	3	9	162
Stability System	Halbach Wheel Function (Active Stability): Enables	Various Metal Components Separate from Halbach Wheel (any combination)	Metal components wi	Manufacturer/fabrication	None - only visual/auditory i	6	3	9	162
Stability System	Halbach Wheel Function (Active Stability): Enables	Halbach Wheel Complete Structural Failure	Magnets/Halbach wh	Manufacturer/fabrication	None - only visual/auditory i	9	2	9	162
Structural System	Rib, Longeron, and Stringer Function: Provides the	Failure of x# Ribs	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	9	2	9	162
Structural System	Rib, Longeron, and Stringer Function: Provides the	Failure of x# Stringers	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	9	2	9	162
Structural System	Rib, Longeron, and Stringer Function: Provides the	Failure of x# Longerons	Pod structural integrit	Manufacturer/fabrication	None - only visual/auditory.	9	2	9	162
Fire Protection System - Pod Interior System	Tank Valve Function: Allows suppression agent to l	Primary Tank Valve Fails to Actuate During Fire Event	Pod interior will only l	Valve degradation, manuf	Gauge on tank valve - no ele	5	4	8	160
Fire Protection System - Pod Interior System	Tank Valve Function: Allows suppression agent to l	Secondary Tank Valve Fails to Actuate During Fire Event	Pod interior will only l	Valve degradation, manuf	Gauge on tank valve - no ele	5	4	8	160
Fire Protection System - Pod Interior System	Detection Tubing Function: Detects fire and contro	Detection Tubing Fails to Actuate Suppression System	Suppression system w	Manufacturer defect or s	Gauge on tank valve - no ele	10	2	8	160
Levitation System	Passive Halbach Array Magnet Function: Enables p	Linear Halbach Array Magnets Get Stuck to Track/Rail	Pod will be immovabl	Significant wheel assembl	Pod position and velocity dat	10	2	8	160
Emergency Braking System - Self Energizing D	Brake Shoe Function: Allows energy transfer to occ	Brake Shoe Overheat - Severe (any axle combination)	No major impact on p	Thermal expansion, rubbi	Thermocouples and thermist	3	5	10	150
Levitation System	Passive Halbach Array Magnet Function: Enables p	Magnets Separate From Linear Halbach Array	Magnets will be eject	Manufacturer/fabrication	None - only visual/auditory i	5	3	10	150
Fire Protection System - Battery Housing	Battery Housing Function (with respect to fire prote	Battery Housing Deforms due to Temperature Differential Upon Agent Releas	Battery housing may r	Temperature differential	None - only visual/auditory c	6	3	8	144

*Please see appendix for full FMEA document.

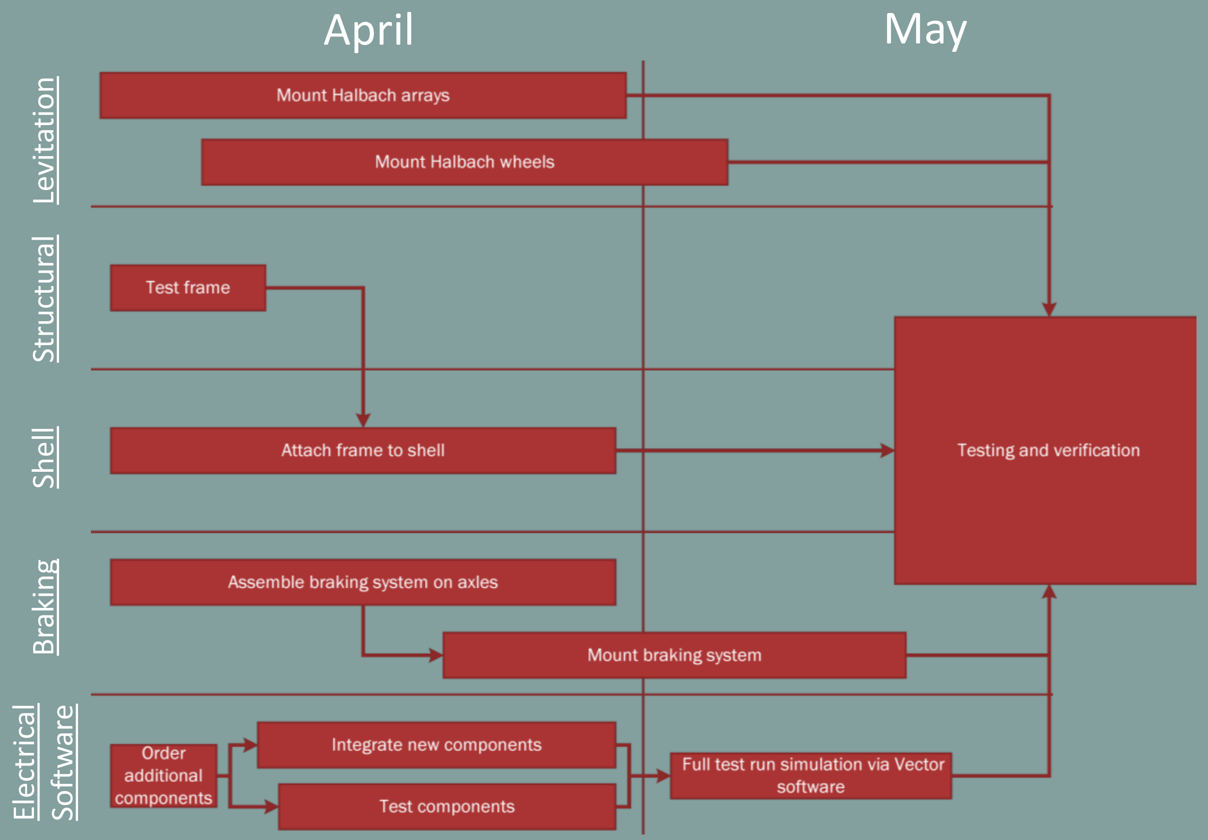
COMPONENT AND SYSTEM TESTING

Subsystem	Component	Test Description
Levitation	Halbach Wheels	Need to verify the force produced by halbach wheels, as well as power consumption. Also test will verify stability of a grouping of motors. Test will include verification of force produced on aluminum rail with the COMSOL model. This will verify our model
Levitation	Halbach Arrays	Testing of Halbach Wheels will verify our COMSOL modeling, but there is not feasible plan to test a full Halbach Array travelling at full speed to obtain levitation of a 1000 [kg] vehicle.
Levitation	Halbach Wheel Motors	Need to verify vacuum compatibility of Halbach Wheel Motors. Test each motor in vacuum chamber for 5 minutes to verify it does not overheat
Levitation	Suspension System	Test will verify the successful damping of our suspension system in a vacuum environment
Levitation	Bearing Wheel System	The pod will be rolled around on the bearing wheels prior to competition to verify the Bearing Wheel system can support the total weight of the pod and spin up to our liftoff velocity
Mechanical	Structure	Simulations with FEA will verify the strength and rigidity of our shell
Mechanical	Structure	Testing will be conducted to ensure the vacuum compatibility of the 3M supertape used to attach much of the carbon fiber shell to the structure
Mechanical	Aerodynamics	Wind tunnel testing will be conducted on the finished shell (sub scale or full scale model) to verify the CFD analysis
Braking	Eddy Brakes	Eddy brakes will be tested via a full scale prototype testing braking force vs. rotor speed to ensure proper braking for the final pod
Braking	Emergency Brakes	Emergency brakes will be tested on a full scale prototype to ensure safe and effective emergency braking
Braking	Deployment System	The deployment system will be tested with the pod stop command to ensure proper deployment of wheels when the stop command is given
Electrical	System-wide	All Data Acquisition, actuator, CAN, and power systems will be fully verified through a case-by-base testing platform to ensure safety and accuracy for the purposes of the competition
Software	System-wide	All code will be run through case-by-case software verification platforms via an application lifecycle management tool

POD CONSTRUCTION TIMELINE



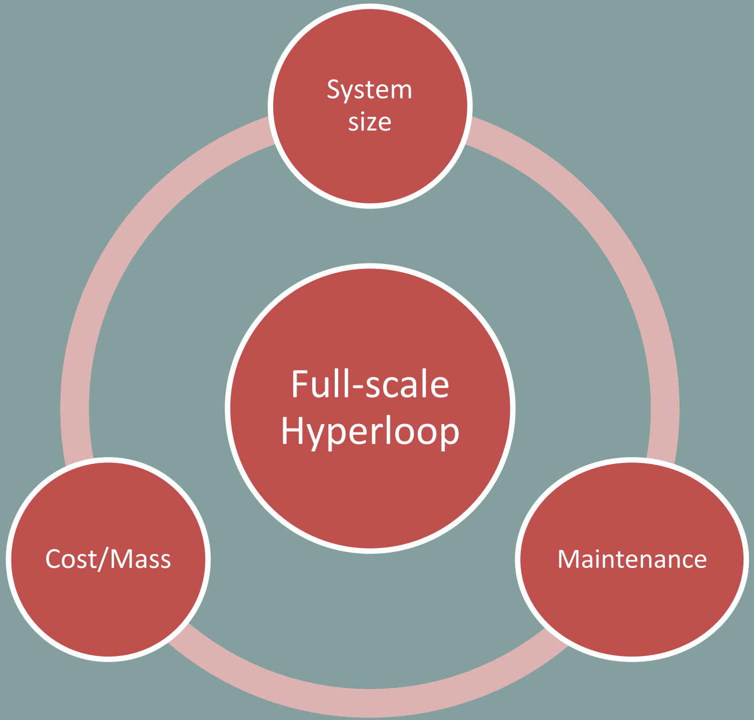
POD CONSTRUCTION TIMELINE



FULL-SCALE BADGERLOOP POD

The BadgerLoop Pod is designed to scale to the specifications laid out in the Hyperloop Alpha paper for a full-scale pod.

We have full confidence that the BadgerLoop pod design is scalable from an economic and engineering standpoint, and could safely and efficiently transport up to 24 people.



FULL-SCALE BADGERLOOP POD – SYSTEM SIZE

Tube Diameter: 7.5 [ft]

- Allows head room for passengers to get into seats

Pod Length: 44.0 [ft]

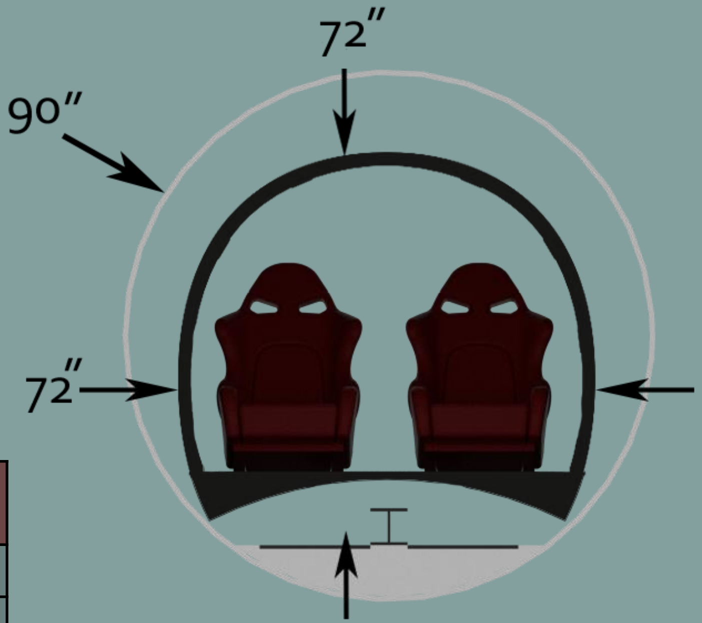
- 24 Passengers in 2 rows
- 8 [ft] designated for nose and rear

Pod Max Width: 6.0 [ft]

- Comfortable room for 2 passengers

Pod Max Height: 6.0 [ft]

- Allows for air flow around pod
- ~5.5 [ft] for passenger head room



	Concept (Hyperloop Alpha)	Competition (BadgerLoop Pod)	Scaled (Full Scale BadgerLoop Pod)
Tube Diameter	7.33 ft	6.0 ft	7.5 ft
Pod Length	-	15.4 ft	44.0 ft
Pod Max Width	4.43 ft	4.7 ft	6.0 ft
Pod Max Height	3.61 ft	4.0 ft	6.0 ft

FULL-SCALE BADGERLOOP POD – MASS & COST

Subsystem	System Mass [kg]	System Cost
Shell and Structure	4000	$240,000.00
Braking System	525	$14,930.00
Levitation System	405	$17,385.00
Stability System	40	$2945.00
Batteries	2000	$150,000.00*
Electrical System	200	$70,000
Safety System	270	$16,150.00
Passenger + Payload	3500	-
TOTAL:	10940	$511,410.00

** Value taken from alpha paper and similar battery mass*

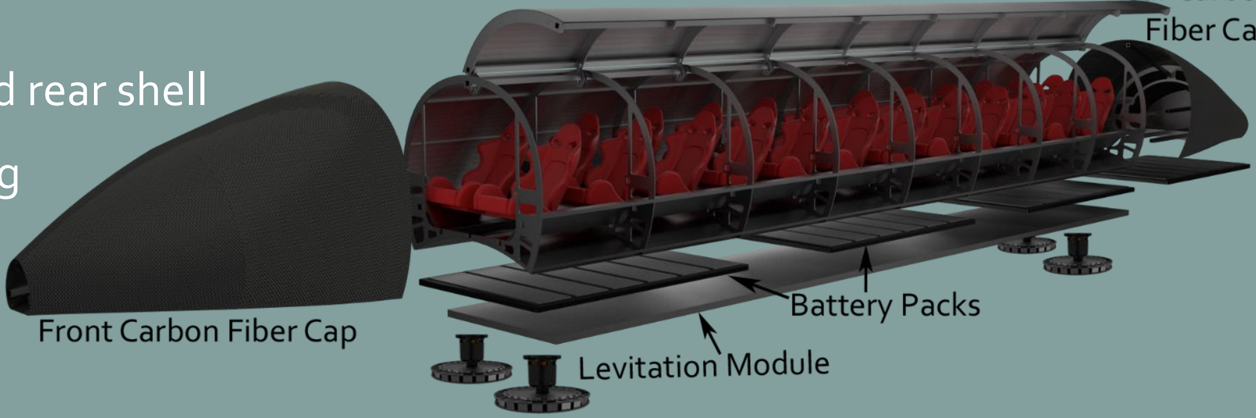
FULL-SCALE BADGERLOOP POD – MAINTENANCE OVERVIEW

- Maintenance similar to existing maglev trains
  - Based off of hours of operation, as opposed to distances traveled.
  - Low maintenance due to lack of mechanical wear
  - No deterioration caused by weather
- Full replacements as opposed to repairs
  - Difficult to “patch” pressure sensitive components
  - Modular construction
    - Allow for replacement of defective module to save cost of replacing entire pod
- Lifecycle similar to aerospace (~20 years)
  - After establishing service, it is budgeted that the equivalence of 2 full pods will need to be replaced per year

FULL-SCALE BADGERLOOP SUBSYSTEMS – SHELL & STRUCTURE

Modular Design

- Made of multiple modules:
  - Aluminum pressure vessel with Aluminum Frame
  - Carbon Fiber nose and rear shell
  - Levitation and Braking system
- Each module can be individually replaced or maintained



FULL-SCALE BADGERLOOP SUBSYSTEMS – BRAKING

The Braking sub-system scales linearly with mass

- Full scale pod will have 5 evenly spaced braking modules

Eddy brakes:

- Do not wear physically
- Require bi-yearly inspection/maintenance

Competition Pod uses aluminum axles to reduce weight. A full-scale pod will use steel axles for repeated use.

FULL-SCALE BADGERLOOP SUBSYSTEMS – LEVITATION MODULES

- Maintenance:
  - Contactless levitation eliminates need for routine maintenance
  - In the case of magnet damage, additional modules available at stations
  - Shocks will wear over time and require replacement

- Halbach arrays contained in steel tubing to prevent shrapnel, should the magnets fracture

FULL-SCALE BADGERLOOP SUBSYSTEMS – INDUCTRACK

Ladder Track

- Track is filled with litz wire
  - Thin transposed wire strands which act as conductors for the Halbach arrays
- More effective lift
- Much more expensive

Laminated Track

- Track is layered with aluminum sheets
  - Sheets are slotted so that current can flow
- Less effective lift
- Much less expensive

Both track types increase the lift to drag ratio of pod compared to a normal sub-track. Badgerloop would use the Laminated aluminum track in an operational hyperloop to reduce cost of the full-scale system.

FULL-SCALE BADGERLOOP POD – NOVEL COUNTER TO SYSTEM DRAG

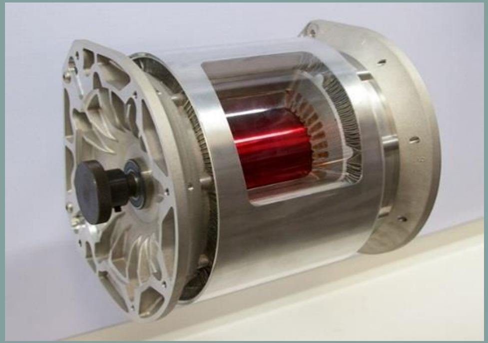
- Halbach wheels are a versatile propulsion system
  - The Halbach Wheel system, along with aerodynamic structure, replaces need for compressor
- Halbach wheels must spin at 13,000 RPM to propel pod at 760mph. Tesla Model S motor has ~360-470hp which implies torque on motor ~145-190 ft*lbs
  - Assumptions
    - 20” diameter Halbach Wheel
    - 4.5 kg disc
    - 760 mph forward velocity
- Single Model S motor horsepower rating ~360-470 hp*
- Inductrack minimizes drag from Halbach array to ~350 N
  - Less Halbach wheels needed (4 wheels for full-scale)
  - 150 L:D ratio based on Halbach array used with inductrack literature cited in appendix

Halbach wheels connected to motors

*https://www.teslamotors.com/blog/tesla-all-wheel-drive-dual-motor-power-and-torque-speifications

FULL-SCALE BADGERLOOP SUBSYSTEMS – HALBACH WHEELS

- Halbach Wheels use Tesla Model S electric Motor
- Turning:
  - Aluminum sub-track facilitates turning
    - Self-centering wheels will naturally align pod to track when turning
    - Halbach arrays will create a torque from banked turns that rotates the pod
  - Halbach wheels utilize independent motors
  - Differential wheel speeds will be used to facilitate turns
- Maintenance:
  - Motors inspected every 12,500 miles on the Tesla Model S
    - Assuming ~310 mile trip for Los Angelos to San Francisco route this translates to ~40 trips
  - Additional wheel modules will be available at stations for hot-swapping if there is wear on Halbach wheels



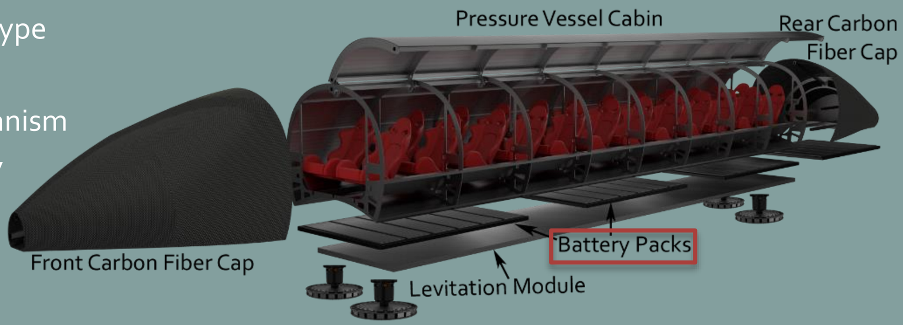
Tesla Model S motor

$$P = \tau\omega$$

Power Calculation Equation

FULL-SCALE BADGERLOOP POD – POWER SYSTEM OVERVIEW

- Ease of integration with Tesla Model S motor and inverter unit enabled by use of Model S battery pack
  - One pack per Halbach wheel
    - Mounted underneath the pressure vessel and above the levitation modules
    - 480 kWh Tesla Model S packs
    - Total energy ~320 kWh
    - Total mass ~2000kg (assuming 500kg per pack)
  - Packs electronically isolated similarly to BadgerLoop pod prototype
  - Packs lie along bottom of pod for equalized weight distribution
- Packs swapped upon arrival to station via external lift and crane mechanism
- Packs charged at station, while charging BMS returns health of battery
  - Bellow acceptable health, battery is removed from cycling
- Quick release high amperage connectors will be used
- Hot-swapping enabled by electronically isolated 48V onboard pack
  - 48V to power pressure vessel and other operational systems including telemetry, navigation, and life support
  - Tesla Model S packs for Halbach wheels discharge at high current to charge 48V before removal



FULL-SCALE BADGERLOOP POD – A SYSTEMS PERSPECTIVE

- Increased demand for influx of Gigafactory infrastructure supply
- Efficiency in using Tesla battery packs
  - Designed to accommodate Tesla Motors for use with Halbach Wheels
  - Standardized, state of the art production
    - Higher production quantities
    - Cheaper production

- Batteries no longer viable for use in Hyperloop utilized for energy storage.
  - Stores energy generated by photovoltaics that line the tube, geothermal beneath the pylons, and other innovative renewable sources

FULL-SCALE BADGERLOOP SUBSYSTEMS – ELECTRICAL

- Controller Area Network (CAN) Communication:
  - Multiple synchronous modules with localized functionality
    - Single module failure does not result in complete system shutdown
  - Inexpensive compared to single CPU necessary full-scale pod
  - Widely used in Industry
    - Large knowledge base
  - Different Pods CAN networks can wirelessly communicate to solve real-time conflict
- System Redundancy:
  - Hardware:
    - Multiple sensors to mitigate effect of faulty sensor
    - Differential signaling
      - Interference is not picked up by CAN bus
      - This prevents errors between network nodes
  - Software:
    - Built in error checking and periodic averaging
    - Cyclic redundancy checking
- Maintenance:
  - Power systems deliver a lot of power in a tight space
    - Produces excess heat and quicker degradation/failure of high-power systems
  - Would require regular inspection

FULL-SCALE BADGERLOOP SUBSYSTEMS – SAFETY

- Pod Safety Features:
  - On-board oxygen tanks ~ $2000
    - Supply to cabin, both primary and secondary, located in different places in the pod in case of fire
  - CO_2 scrubbers ~ $150
    - Used to prevent toxicity from CO_2 buildup
    - Would need to be periodically resupplied
  - Carbon monoxide detectors ~ $100
    - Redundancy for fire protection system
  - Dropdown oxygen masks ~ $500
    - For the case of pod depressurization
  - First aid/survival kits ~ $300
    - In easily accessible locations throughout the cabin
  - Cabin pressure and atmospheric monitoring sensors ~ $600
    - Trigger secondary oxygen supply in case of low-oxygen situations
  - Hydraulics systems built into passenger chairs ~ $6,000
    - Mounted to pod floor to absorb rapid stop impact forces
    - Possibly orient passengers backwards to reduce force on restraint systems
  - Concealed seat belt restraint system ~ $1500
    - For emergency situations when the pod becomes unstable, over speeds, or begins to under speed
  - Emergency exit hatches on the top and bottom of the pod ~ $12000 (does not include cost to build exits on tube)
    - Will line up with and dock with emergency hatches built into the tube.
  - Airbags ~ $4000
    - Interior sides of the pod and on the seat/wall in front of every passenger
- Approximate Full-scale System Cost: $16,150
- All systems will be checked for maintenance at least 3 times a year

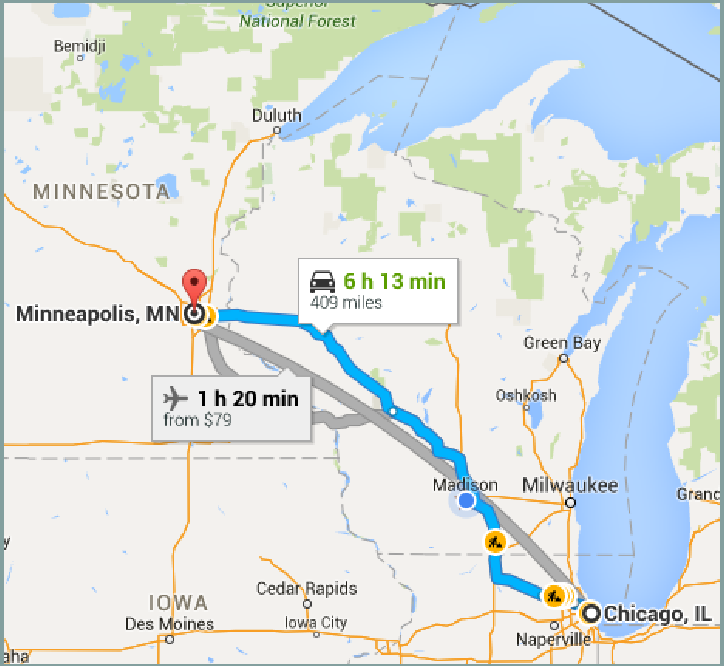
FULL-SCALE BADGERLOOP SUBSYSTEMS – SAFETY PROTOCOLS

- Medical Emergency
  - Emergency Medical Services are contacted while pod is still in motion and pod continues to nearest destination
  - Meet personnel at station
- Wide scale external linear induction motor failure
  - Halbach wheels function of primary propulsion while pod safely decelerates
- Pod Stuck in Tube
  - Pod either transmits GPS coordinates or gives a pylon number – similar to utility poles – so that emergency response personnel can directly locate and access the pod

HYPERLOOP IN THE MIDWEST

Midwest = "Flyover Zone." Hyperloop could change that.

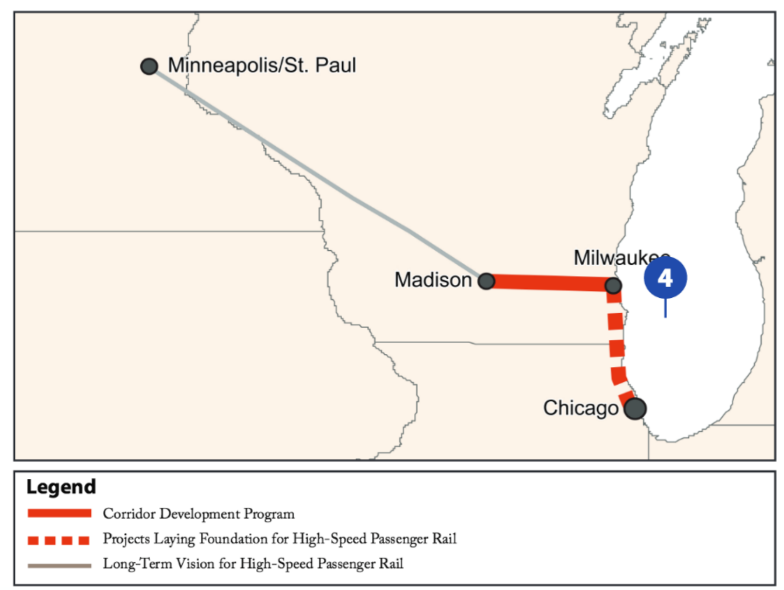
- 409 miles between Chicago and Minneapolis
- 6+ hour drive
- ~1.5 hour flight
- 45 minute hyperloop
  - Similar distance as LA to SF
  - More curves = slower speeds



HYPERLOOP IN THE MIDWEST

High-Speed Intercity Passenger Rail Program

- Proposed in 2010
- Implementation would have secured $810 million in federal stimulus money
- Plan to connect Chicago to Milwaukee to Madison to Minneapolis/St. Paul
- Program well developed at time of cancellation
  - Route researched
  - Use research to develop optimal hyperloop route



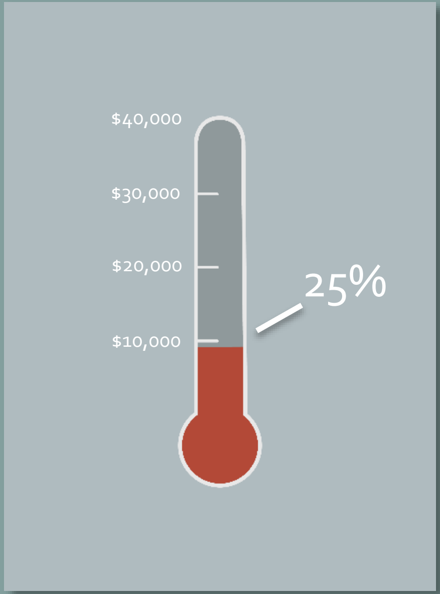
FULL-SCALE BADGERLOOP – LOOKING AHEAD

- Centralized tube design to accommodate pods from different providers
  - The NYC subway system has famously been developed around two rail types from competing companies
    - Manhattan Transportation Authority still must buy two different types of cars to accommodate*
    - Developing a uniform infrastructure for multiple companies to utilize
- The BadgerLoop Pod is designed to be scalable and affordable for an operational Hyperloop

*http://web.mta.info/mta/budget/pdf/MTA%202015%20Adopted%20Budget%20February%20Financial%20Plan%202015-2018.pdf

FUNDRAISING

- We have raised just over $10,000 to date, approximately 25% of our overall budget
- Current Sponsors:



CONCLUSION

Exceptional aerodynamics, innovative levitation, efficient control and sensor networks, modular design, and a team that refuses to quit.

We are BadgerLoop, and we will revolutionize transportation.

REFERENCES

- Bird, J. 2007. *An Investigation Into the Use of Electrodynamic Wheels for High-Speed Ground Transportation*. University of Wisconsin-Madison
- Murai, Toshiaki., Hasegawa, Hitoshi. 2003. *Electromagnetic Analysis of Inductrack Magnetic Levitation.* Electrical Engineering in Japan 142, no. 1
- Musk, E. 2013. *Hyperloop Alpha*. SpaceX, California, United States.
- Post, R. F., Gurol, S., Baldi, B., 2005 *The General Atomics Low Speed Urban Maglev Technology Development Program*. General Atomics and Lawrence Livermore National Laboratory
- Post, R. F., Nguyen, L. 2012. *The Design of Halbach Arrays for Inductrack Maglev Systems*
- Post, R. F., RYUTOV, D. 2004. *The Inductrack Approach to Magnetic Levitation*
- SpaceX, 2015. *SpaceX Hyperloop Specification*. SpaceX, California, United States
- Tesla Motors, 2014, *Tesla Model S Brochure*. Tesla Motors, California, United States
- Tesla Motors, 2015, *Tesla Model S Brochure*. Tesla Motors, California, United States

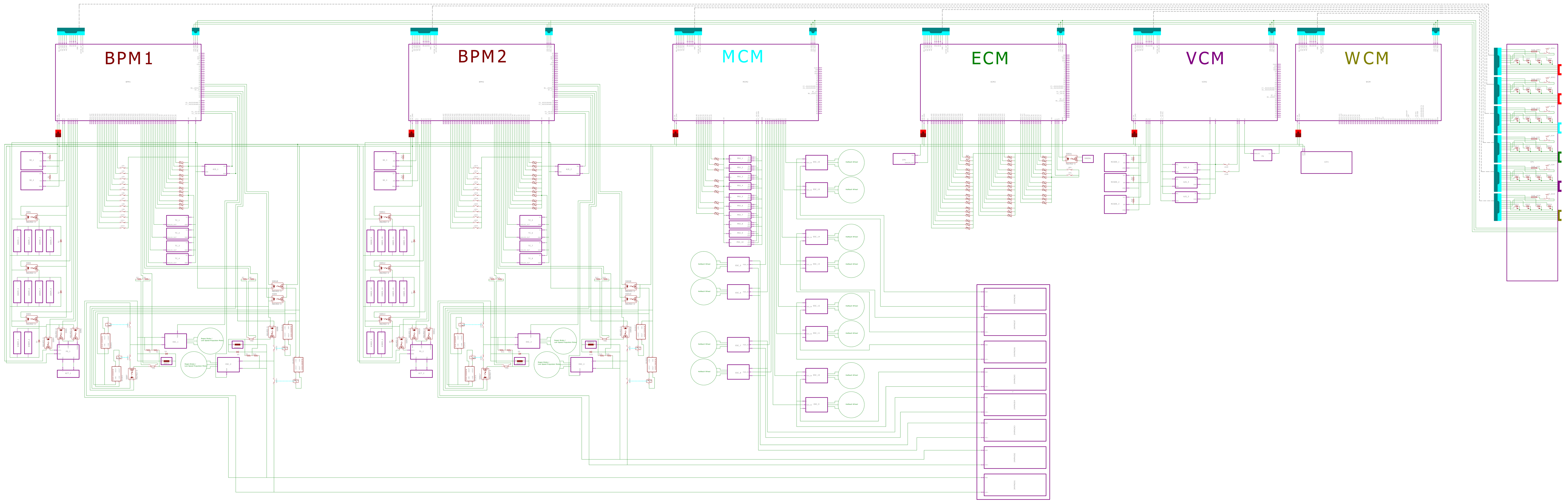
BadgerLoop Appendix

Content

Appendix A: Electrical System Schematic Key.................2

Appendix B: Electrical System Schematic Overview.........3

BPM 1		BPM 2		MCM		ECM		VCM	
SE_1		SE_3	Shaft Encoder 3	T25	Thermistor 25	CPS	Cabin Pressure Sensor	RCSDE_1	Retroreflective Color Strip Sensor 1
SE_2	Shaft Encoder 2	SE_4	Shaft Encoder 4	T26	Thermistor 26	T34	Thermistor 34	RCSDE_2	Retroreflective Color Strip Sensor 2
R1	Resistor 1	R11	Resistor 11	T27	Thermistor 27	T35	Thermistor 35	RCSDE_3	Retroreflective Color Strip Sensor 3
R2	Resistor 2	R12	Resistor 12	T28	Thermistor 28	T36	Thermistor 36	R21	Resistor 21
R3	Resistor 3	R13	Resistor 13	T29	Thermistor 29	T37	Thermistor 37	R22	Resistor 22
R4	Resistor 4	R14	Resistor 14	T30	Thermistor 30	T38	Thermistor 38	R23	Resistor 23
R5	Resistor 5	R15	Resistor 15	T31	Thermistor 31	T39	Thermistor 39	A/G_3	Accelerometer / Gyroscope 3
R6	Resistor 6	R16	Resistor 16	T32	Thermistor 32	T40	Thermistor 40	A/G_4	Accelerometer / Gyroscope 4
R7	Resistor 7	R17	Resistor 17	T33	Thermistor 33	T41	Thermistor 41	A/G_5	Accelerometer / Gyroscope 5
R8	Resistor 8	R18	Resistor 18	PRX_1	Proximity Sensor 1	T42	Thermistor 42	LS25	Limit Switch 25
R9	Resistor 9	R19	Resistor 19	PRX_2	Proximity Sensor 2	T43	Thermistor 43	LS26	Limit Switch 26
R10	Resistor 10	R20	Resistor 20	PRX_3	Proximity Sensor 3	T44	Thermistor 44	FS	Force Sensor
SSR1	Solid State Relay 1	SSR11	Solid State Relay 11	PRX_4	Proximity Sensor 4	T45	Thermistor 45		
SSR2	Solid State Relay 2	SSR12	Solid State Relay 12	PRX_5	Proximity Sensor 5	T46	Thermistor 46		
SSR3	Solid State Relay 3	SSR13	Solid State Relay 13	PRX_6	Proximity Sensor 6	T47	Thermistor 47		
SSR4	Solid State Relay 4	SSR14	Solid State Relay 14	PRX_7	Proximity Sensor 7	T48	Thermistor 48		
SSR5	Solid State Relay 5	SSR15	Solid State Relay 15	PRX_8	Proximity Sensor 8	T49	Thermistor 49		
SSR6	Solid State Relay 6	SSR16	Solid State Relay 16	PRX_9	Proximity Sensor 9	T50	Thermistor 50		
SSR7	Solid State Relay 7	SSR17	Solid State Relay 17	PRX_10	Proximity Sensor 10	T51	Thermistor 51		
SSR8	Solid State Relay 8	SSR18	Solid State Relay 18	ESC_5	Electronic Speed Controller 5	T52	Thermistor 52		
SSR9	Solid State Relay 9	SSR19	Solid State Relay 19	ESC_6	Electronic Speed Controller 6	T53	Thermistor 53		
SSR10	Solid State Relay 10	SSR20	Solid State Relay 20	ESC_7	Electronic Speed Controller 7	T54	Thermistor 54		
DBEM_1	Drum Brake Eddy Magnet 1	DBEM_9	Drum Brake Eddy Magnet 9	ESC_8	Electronic Speed Controller 8	T55	Thermistor 55		
DBEM_2	Drum Brake Eddy Magnet 2	DBEM_10	Drum Brake Eddy Magnet 10	ESC_9	Electronic Speed Controller 9	T56	Thermistor 56		
DBEM_3	Drum Brake Eddy Magnet 3	DBEM_11	Drum Brake Eddy Magnet 11	ESC_10	Electronic Speed Controller 10	T57	Thermistor 57		
DBEM_4	Drum Brake Eddy Magnet 4	DBEM_12	Drum Brake Eddy Magnet 12	ESC_11	Electronic Speed Controller 11	T58	Thermistor 58		
DBEM_5	Drum Brake Eddy Magnet 5	DBEM_13	Drum Brake Eddy Magnet 13	ESC_12	Electronic Speed Controller 12	T59	Thermistor 59		
DBEM_6	Drum Brake Eddy Magnet 6	DBEM_14	Drum Brake Eddy Magnet 14	ESC_13	Electronic Speed Controller 13	T60	Thermistor 60		
DBEM_7	Drum Brake Eddy Magnet 7	DBEM_15	Drum Brake Eddy Magnet 15	ESC_14	Electronic Speed Controller 14	T61	Thermistor 61		
DBEM_8	Drum Brake Eddy Magnet 8	DBEM_16	Drum Brake Eddy Magnet 16	ESC_15	Electronic Speed Controller 15	T62	Thermistor 62		
D1	Diode 1	D6	Diode 6	ESC_16	Electronic Speed Controller 16	T63	Thermistor 63		
D2	Diode 2	D7	Diode 7			T64	Thermistor 64		
D3	Diode 3	D8	Diode 8			T65	Thermistor 65		
D4	Diode 4	D9	Diode 9			T66	Thermistor 66		
D5	Diode 5	D10	Diode 10			T67	Thermistor 67		
WBEM_1	Wheel Bogie Electromagnet 1	WBEM_3	Wheel Bogie Electromagnet 3			T68	Thermistor 68		
WBEM_2	Wheel Bogie Electromagnet 2	WBEM_4	Wheel Bogie Electromagnet 4			T69	Thermistor 69		
PS_1	Polarity Switcher 1	PS_2	Polarity Switcher 2			T70	Thermistor 70		
ACT_1	Linear Actuator 1	ACT_2	Linear Actuator 2			T71	Thermistor 71		
LS1	Limit Switch 1	LS13	Limit Switch 13			T72	Thermistor 72		
LS2	Limit Switch 2	LS14	Limit Switch 14			T73	Thermistor 73		
LS3	Limit Switch 3	LS15	Limit Switch 15			T74	Thermistor 74		
LS4	Limit Switch 4	LS16	Limit Switch 16			T75	Thermistor 75		
LS5	Limit Switch 5	LS17	Limit Switch 17			T76	Thermistor 76		
LS6	Limit Switch 6	LS18	Limit Switch 18			T77	Thermistor 77		
LS7	Limit Switch 7	LS19	Limit Switch 19			T78	Thermistor 78		
LS8	Limit Switch 8	LS20	Limit Switch 20			BFS	Battery Fire Pressure Sensor		
LS9	Limit Switch 9	LS21	Limit Switch 21			CFS	Cabin Fire Pressure Sensor		
LS10	Limit Switch 10	LS22	Limit Switch 22			SSR21	Solid State Relay 21		
LS11	Limit Switch 11	LS23	Limit Switch 23						
LS12	Limit Switch 12	LS24	Limit Switch 24						
EMR1	Electromagnetic Relay 1	EMR5	Electromagnetic Relay 5						
EMR2	Electromagnetic Relay 2	EMR6	Electromagnetic Relay 6						
EMR3	Electromagnetic Relay 3	EMR7	Electromagnetic Relay 7						
EMR4	Electromagnetic Relay 4	EMR8	Electromagnetic Relay 8						
DC/DC1	DC/DC Converter 1	DC/DC5	DC/DC Converter 5						
DC/DC2	DC/DC Converter 2	DC/DC6	DC/DC Converter 6						
DC/DC3	DC/DC Converter 3	DC/DC7	DC/DC Converter 7						
DC/DC4	DC/DC Converter 4	DC/DC8	DC/DC Converter 8						
CS1	Current Shunt 1	CS3	Current Shunt 3						
CS2	Current Shunt 2	CS4	Current Shunt 4						
ESC_1	Electronic Speed Controller 1	ESC_3	Electronic Speed Controller 3						
ESC_2	Electronic Speed Controller 2	ESC_4	Electronic Speed Controller 4						
EDDY1	Eddy Magnet 1	EDDY3	Eddy Magnet 3						
EDDY2	Eddy Magnet 2	EDDY4	Eddy Magnet 4						
T1	Thermistor 1	T13	Thermistor 13						
T2	Thermistor 2	T14	Thermistor 14						
T3	Thermistor 3	T15	Thermistor 15						
T4	Thermistor 4	T16	Thermistor 16						
T5	Thermistor 5	T17	Thermistor 17						
T6	Thermistor 6	T18	Thermistor 18						
T7	Thermistor 7	T19	Thermistor 19						
T8	Thermistor 8	T20	Thermistor 20						
T9	Thermistor 9	T21	Thermistor 21						
T10	Thermistor 10	T22	Thermistor 22						
T11	Thermistor 11	T23	Thermistor 23						
T12	Thermistor 12	T24	Thermistor 24						
TC_1	Thermocouple 1	TC_5	Thermocouple 5						
TC_2	Thermocouple 2	TC_6	Thermocouple 6						
TC_3	Thermocouple 3	TC_7	Thermocouple 7						
TC_4	Thermocouple 4	TC_8	Thermocouple 8						
A/G_1	Accelerometer / Gyroscope 1	A/G_2	Accelerometer / Gyroscope 2						



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