SpaceX Hyperloop Test-Track Specification

Revision 9.0

September 28, 2016

CONTENTS

1 INTRODUCTION

On August 12, 2013, Elon Musk released a white paper on the Hyperloop, his concept of high-speed ground transport. In order to accelerate the development of a functional prototype and to encourage student innovation, SpaceX is moving forward with a competition to design and build a Hyperloop Pod. In parallel with the competition, SpaceX will be constructing a sub-scale test track adjacent to its Hawthorne, California headquarters. During Design Weekend in January 2016, entrants will submit and present their Pod designs. On Competition Weekend, scheduled for January 2017, entrants will operate their Pods within the SpaceX test track.

This document contains the technical specifications for the test track that SpaceX will build to support Competition Weekend. As this is the first Hyperloop ever built, it is likely that small changes will occur during the construction process.

Note: This competition is a SpaceX event. *SpaceX has no affiliation with any Hyperloop companies, including, but not limited to, those frequently referenced by the media.*

Any questions or comments should be submitted to Hyperloop@spacex.com.

2 STRUCTURAL

The test track will be a steel tube, fitted with an aluminum sub-track and rail mounted to a concrete fill bed. At the tube's egress door, there is a "foam pit" to help mitigate the {hopefully non-occurring} case of a Pod braking system failure. The tube sections will rest on concrete cradles, reinforced with steel and fitted with PTFE slip bearings.

The parameters of the Hyperloop test track are:

- Material: ASTM A1018 Grade 36
- Outer diameter: 72.0 inches
- Inner diameter: 70.6 inches
- Wall thickness: 0.70 inches
- Length: Between 4150 and 5000 feet (1.25 and 1.51 km)
- Radius of curvature: Greater than 15 miles (24 km) at all points
- Instantaneous bends: Less than 0.16° in pitch and 0.07° in yaw
- Subtrack material: Aluminum 6101-T61
- Subtrack roughness: 125 RMS with potential for occasional surface scratches up to 0.008"
- Subtrack thickness: 0.5 inches
- Concrete height: 10.4 inches
- Rail material: Aluminum 6061-T6
- Internal pressure: 0.125 – 14.7 PSI (see note at end of section)

All critical dimensions and tolerances are outlined on the drawing on Page 5. Please note that the latest drawing revision will always supersede the following reference notes:

- The flatness profile per unit square is 0.04". This means that local undulations of the plate as installed will be 0.04" or less over a 15" x 15" square.
- The maximum variation of the top plane of the track relative to the theoretical center point of the tube is +/-0.4". Important to note is that this variation does not mean you could have an abrupt step, as the maximum slope of the track in the longitudinal direction is limited to 0.04" per foot.
- Maximum slope of the track in the lateral direction is covered by the parallelism callout and will be 0.06" per subtrack plate.
- See drawing for smoothness values for pipe section joint and helical pipe weld.
- SpaceX will potentially coat the aluminum in order to increase its smoothness.
- SpaceX is working on optimizing the overall plate lengths and installation gaps. The current baseline is a gap pitch of every 12.5 feet with a maximum gap size of 0.1" to 0.125". We will strive to reduce the gap size to 0.05" for the first several hundred feet of the track. Gaps may or may not be filled with a non-conductive flexible filler. Maximum steps in height between plates on the track will be limited to 0.04" or less.

The test track is designed to be flexible and to allow competitors to implement, at a minimum, the following three types of levitation/suspension:

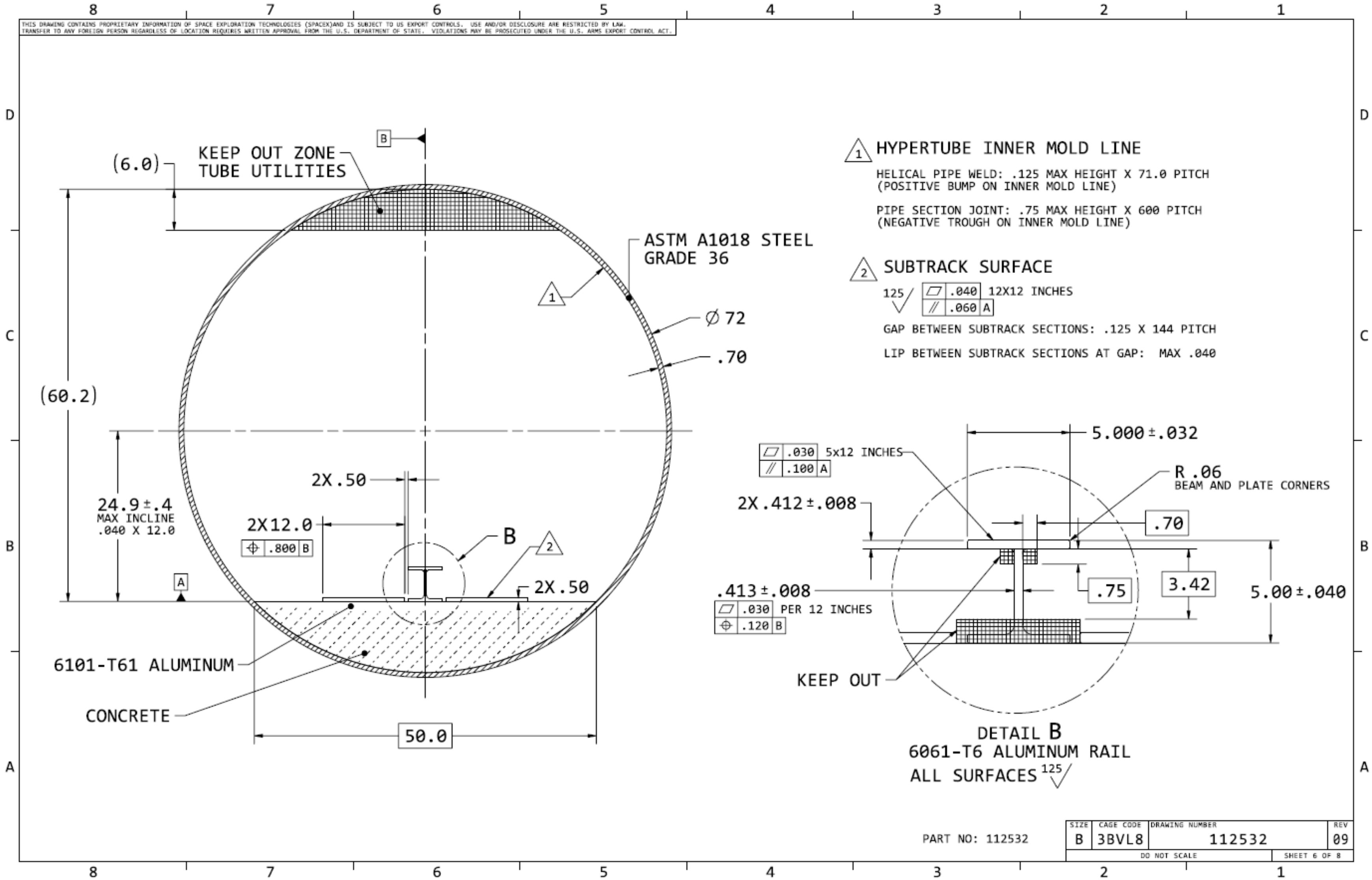
1. Wheels: The concrete flat section along the outside allow for a good wheel surface and aluminum rail(s) allow for horizontally oriented wheels, as implemented on certain roller coasters.
2. Air Bearings: The aluminum plate allows for a much smoother and flatter surface than the steel tube itself. The rail(s) can be used for lateral control, either through side-mounted bearings or wheels.
3. Magnetic levitation: Several forms of magnetic levitation require a conductive non-magnetic surface (e.g. copper or aluminum). The sub-track allows for magnetic levitation and the rail(s) allow for lateral control.

Notes on Tube Pressure and Temperature

Per parameters above, the internal pressure of the tube shall be between 0.125 – 14.7 psi. In order to support various types of propulsion systems, compressors (if applicable), and outer mold lines, the Pod team may select the tube's operating pressure from within that range (pending SpaceX approval).

The test track will not include a thermal control system, so tube temperatures will vary based on the time of day and weather. Teams request their specific operating pressure in the tube, but should be aware that at lower pressures, cooling by convection will become very inefficient. Designs without careful consideration or mitigation of thermal hotspots may not be able to survive the vacuum pumpdown time. The pumpdown period to reach the minimum pressure rating of 0.125 psi will likely be 25-35 minutes. The repressurization period will be less than 5 minutes.

Subtrack: Aluminum subtrack with central rail (all dimensions in inches)



3 PROPULSION SYSTEM AND INTERFACE

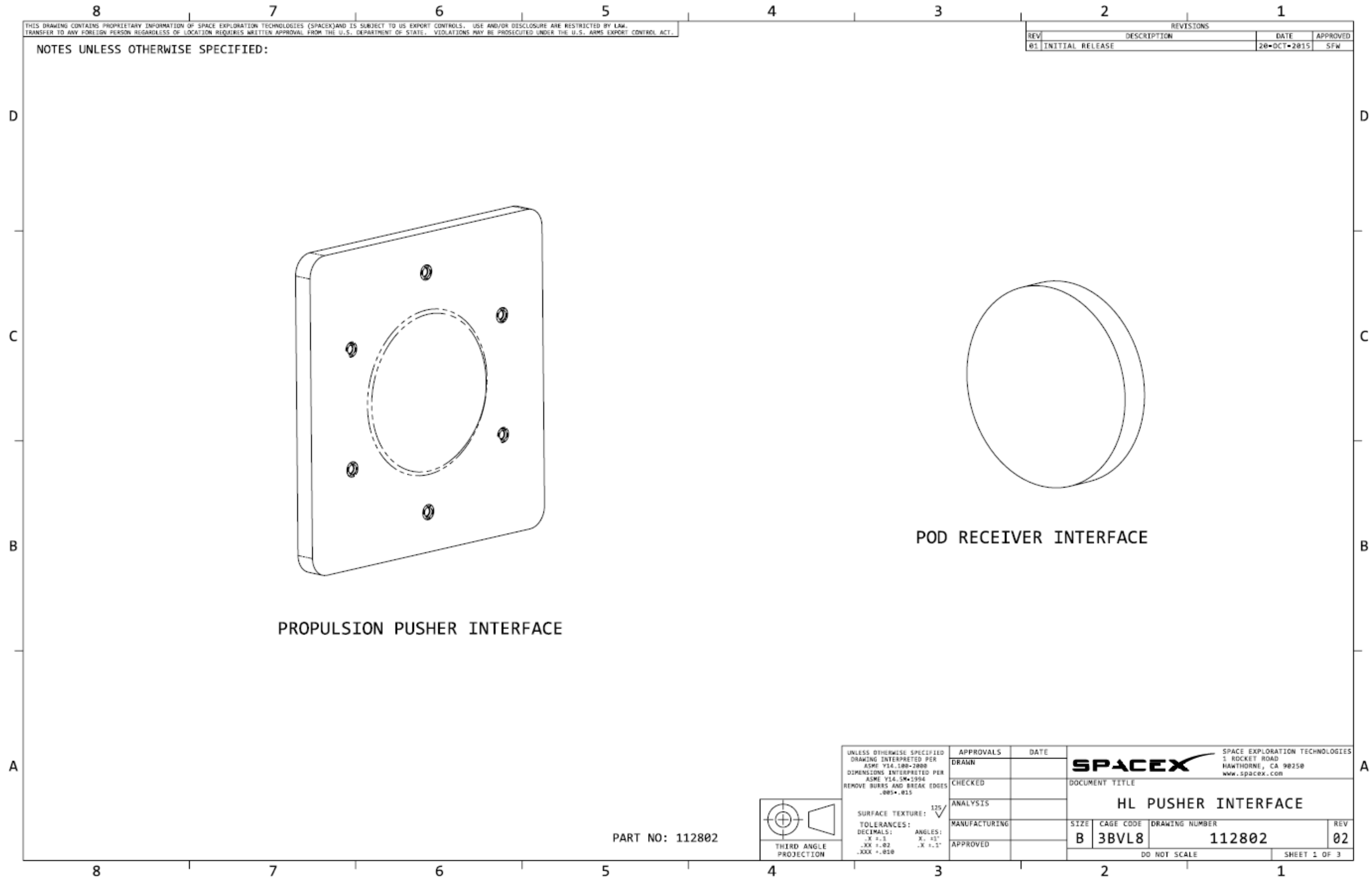
The test track will not be fitted with a structurally integrated propulsion system. Instead, teams have three options with regards to initial propulsion:

1. *On-Pod Propulsion System.* This can take for the form of a drive train for wheels, magnetic repulsion, or compressed gas (stored or from turbine). For all cases, entrants can specify the tube's operating pressure to help optimize their system.
2. *Off-Pod Propulsion System.* Teams can work with SpaceX to create their own system, which we can integrate into the tube for that Pod's specific run (applies to specific Pod designs).
3. *SpaceX Pusher.* SpaceX will construct a high-power wheeled vehicle and attach an interface plate to the front, which can then push Pods up to speed.
    a. The Propulsion Pusher Interface (PPI) consists of a pusher plate with a spherical contact interface, which will be laterally centered in the tube. The Pod Receiver Interface (PRI) is simply a flat plate. See diagrams on the next three pages.
    b. The height of the sphere center can be adjusted, in 1.0-inch increments, between 10 and 20 inches above the aluminum subtrack, as specified by each Pod team.
    c. The PPI will not float vertically. To accommodate levitation after contact, the PPI will slide on the PRI. Teams should specify their desired PPI height on the SpaceX Pusher.
    d. For teams interested in a non-standard pusher interface, there are 6 quarter inch inserts in a 6 inch diameter circle on the SpaceX cone side of the interface. Teams may choose to manufacture and bring both sides of their pusher/pod interface joint and mount their pusher side to the SpaceX interface prior to competition. Pre-coordination is required with SpaceX prior to building a custom launch mount. In general, these shall have a weight less than 10 pounds, a length less than 12 inches from the surface of the plate, and the team shall bring their own fastening hardware.
    e. Maximum displacement for the acceleration profile is 1600 feet.
    f. Each Pod acceleration profile has to be approved by SpaceX on a case-by-case basis. Representative pusher acceleration values are shown in the table on the next page. It is likely that Pods are started at lower acceleration values than shown in the table.
    g. Each Pod utilizing this pusher will have to demonstrate mass distributions and separation dynamics to ensure a straight push with limited separation moment.
    h. Maximum velocities will be determined based on final Pod designs and will be capped in order to make the Judging Criteria fair amongst Pods of different masses.
    i. The SpaceX Pusher specification will likely not be finalized until early 2016. Thus, Pod teams who utilize this system do face the risk of small interface modifications, and thus should ensure their mechanical interface remains flexible.
    j. The Pod should be designed such that the PRI is normal to the rail (i.e. the cone is parallel to the tube axis). There should be no more than +/- 2.5° error relative to the nominal parallelism.
    k. Pods utilizing the SpaceX Pusher should not protrude aft of the interface plane in order to avoid mechanical interference. Teams have the option to construct an adapter that attaches to the PPI in order to extend its length (as noted in Item d above).

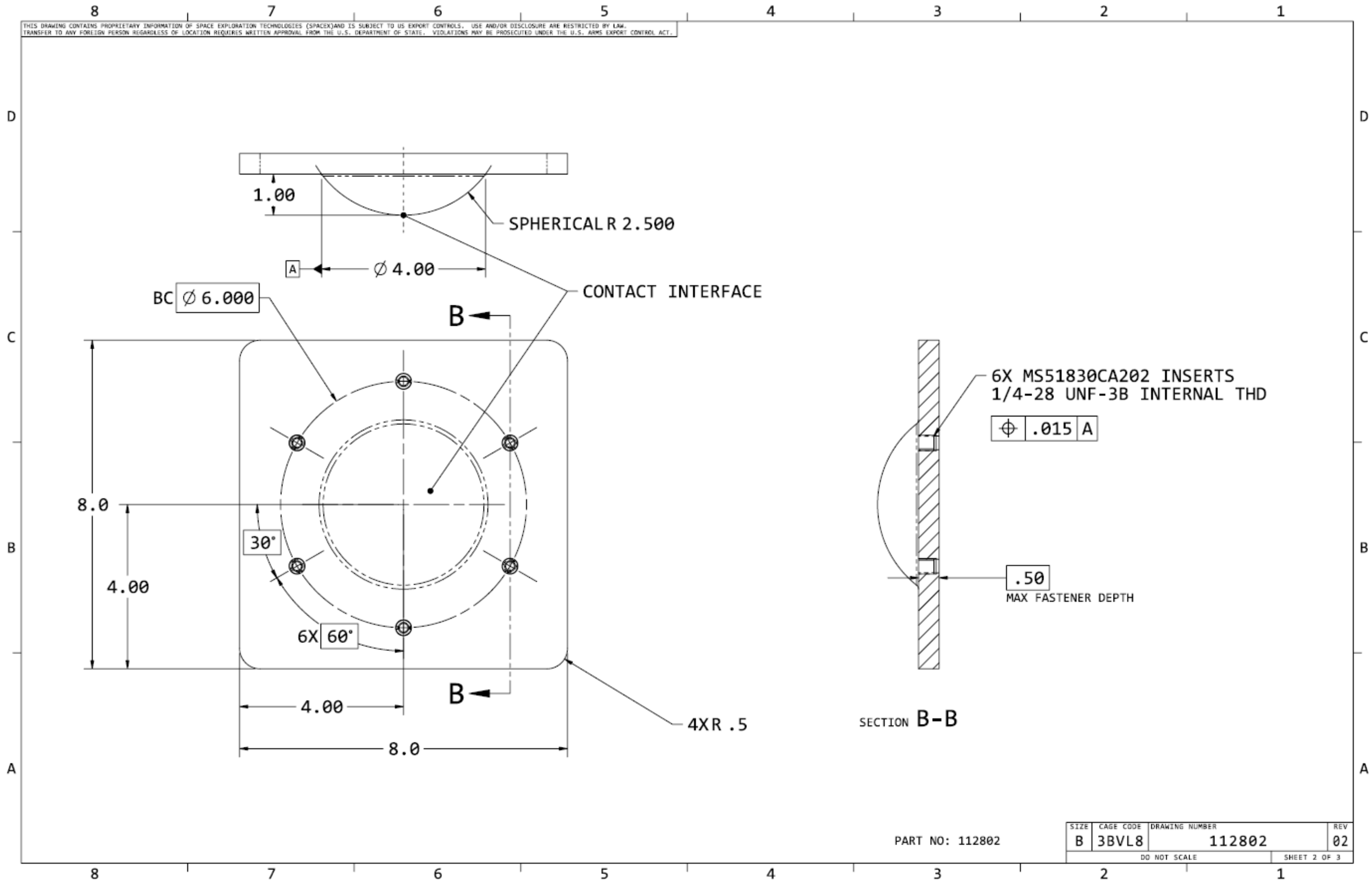
Representative pusher acceleration values. Please note that, in the initial 2016 competition, SpaceX will likely limit student Pod accelerations to lower values.

Pod Mass (kg)	Pod Mass (lbm)	Pod Acceleration (g)
250	550	2.4
500	1100	2.0
750	1650	1.7
1000	2200	1.5
1500	3300	1.2
2000	4400	1.0
2500	5500	0.9
3000	6600	0.8
4000	8800	0.6
5000	11000	0.5

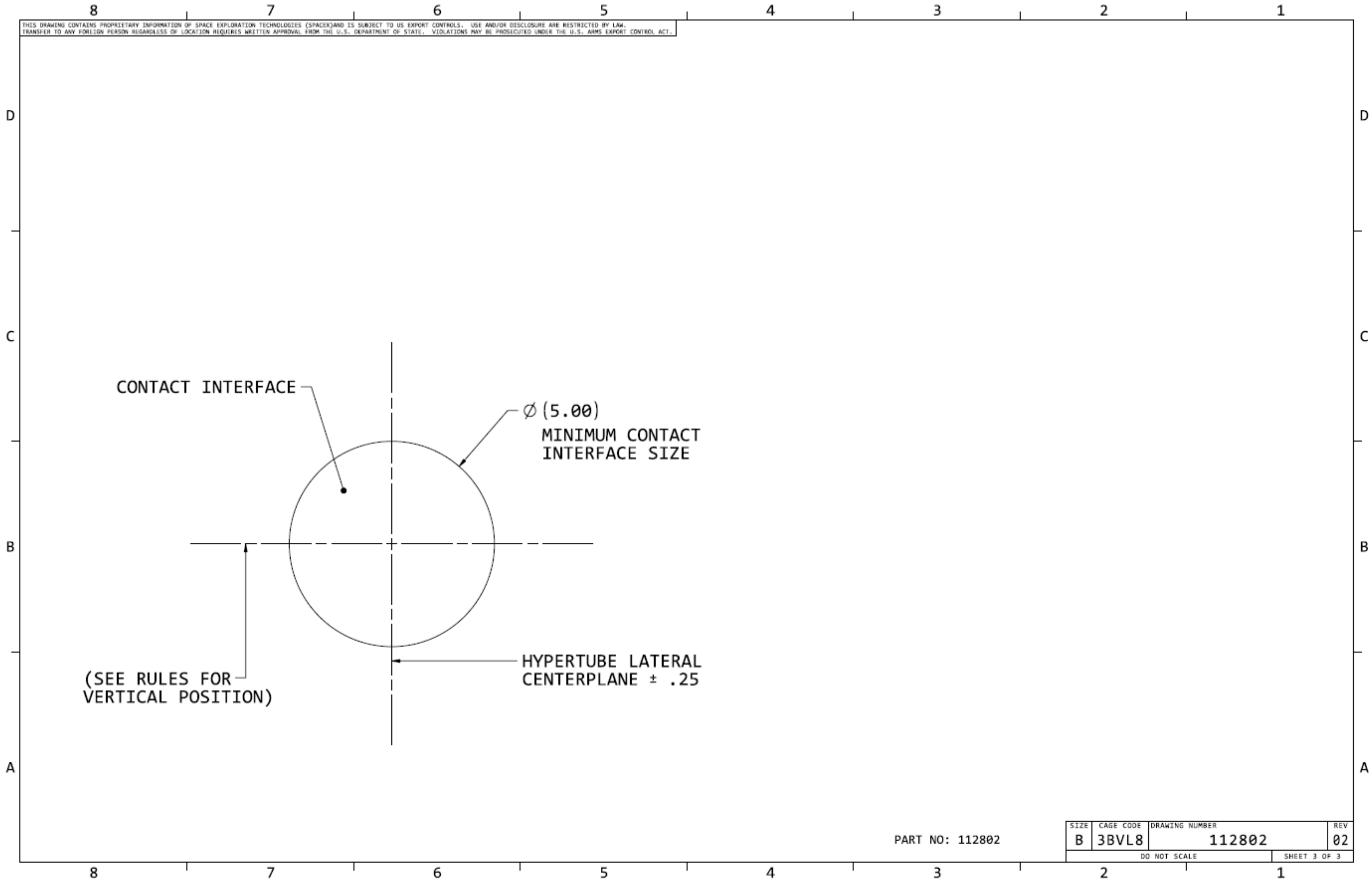
Pusher Interface (1 of 3) (all dimensions in inches)



Pusher Interface (2 of 3) (all dimensions in inches)



Pusher Interface (3 of 3) (all dimensions in inches)



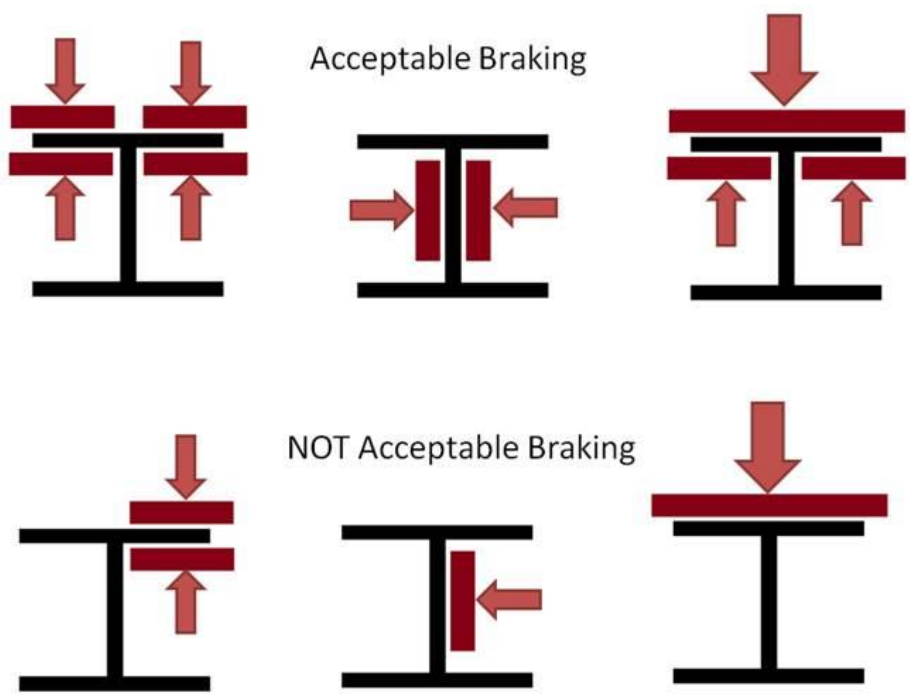
4 BRAKING SYSTEM

Besides the emergency "foam pit," no braking system will be provided by SpaceX. Pods are therefore responsible for their own braking system in order to slow down near the end of the Hyperloop test track. Subject to the restrictions below, frictional braking techniques are allowed - braking may be performed with reaction against the steel tube, concrete base, aluminum subtrack, or central rail.

All braking operations shall be designed to minimize damage to the track surface used for braking by abiding by these rules:

- Material in contact with the track shall be of a lower hardness than the track component
- Material in contact with the track shall be designed to wear as opposed to stick/slip
- Teams shall demonstrate by analysis that their braking system will not inadvertently "lock up" and cause an abrupt stop
- Teams shall demonstrate by analysis that their braking system will accommodate steps and tolerance variations in the track without braking system failure

All braking operations using the central rail must be self-reacted and symmetric about the rail. In other words, the braking operation must clamp the rail with opposing brake pads instead of pushing a single pad against the rail, and the pod must brake using both flange sections or neither. Friction braking systems using the central rail or aluminum subtrack shall not provide deceleration of greater magnitude than the acceleration values provided by the SpaceX pusher vehicle for the Pod mass. The deceleration profiles must be approved by SpaceX, with lower decelerations generally encouraged when feasible.



5 POWER

In general, Pod power shall be provided on the Pod itself and there is no auxiliary electric rail in the test track. However, external power will be available in two areas:

Pod Waiting Area

This is the area where all Pods are located before and after their run. Power available will be:

- 240 VAC at up to 50 A (single phase, 60 hz)(NEMA 14-50 receptacle)
- 110 VAC at up to 15 A (single phase, 60 hz)(NEMA 5-15 receptacle)

Teams may bring their own equipment as well to power/charge their Pods in the Pod Waiting Area.

Pre-Launch Phase within Tube

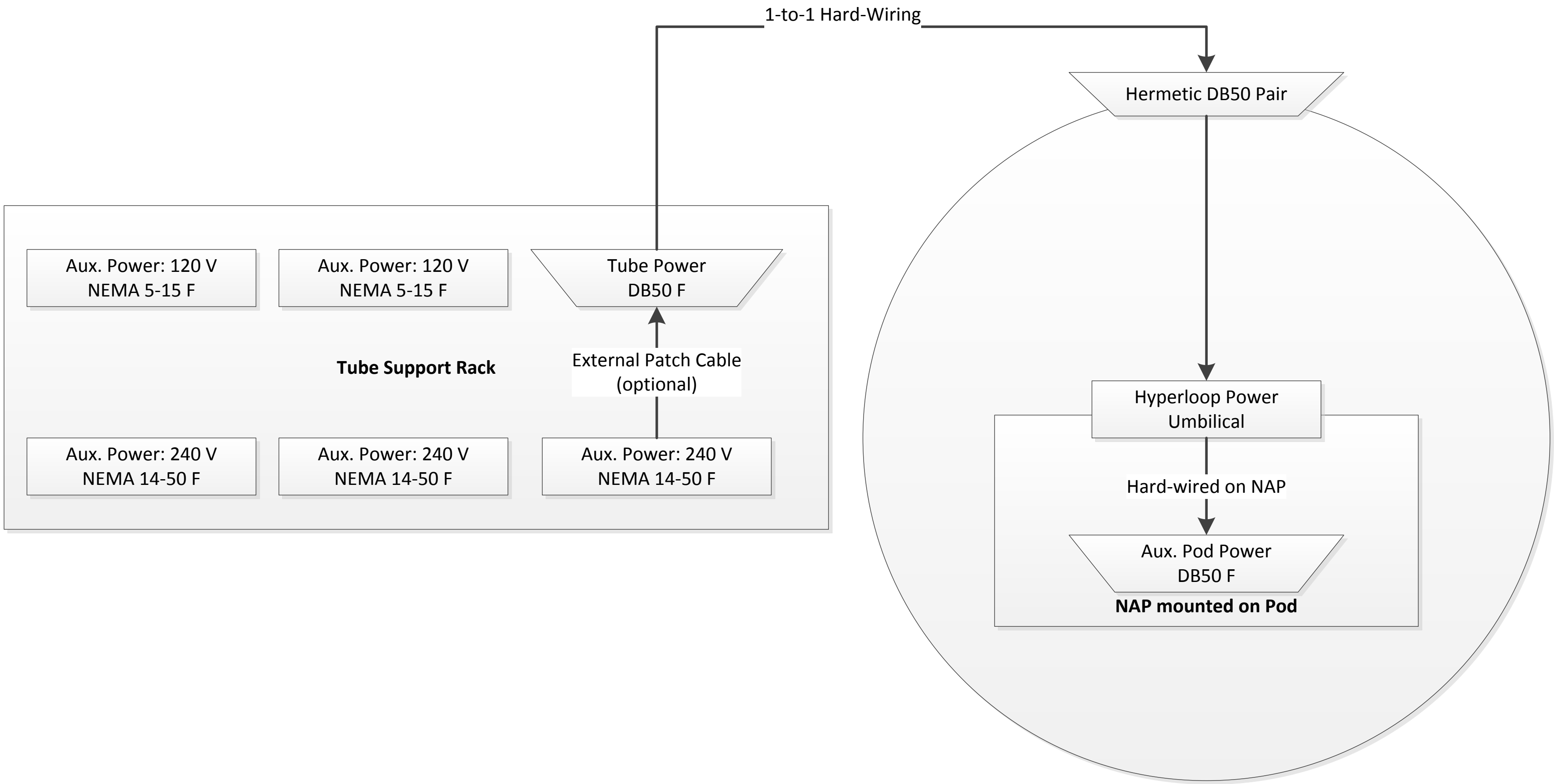
For the pre-launch phases, SpaceX will provide a quick-disconnect electrical umbilical, known as the Hyperloop Power Umbilical. It will be connected to the Pod's Network Access Panel (see Communications section) once the Pod has been loaded into the tube from the Staging Area. It will be a standard electrical connector with a lanyard release mechanism. The separation event will occur before the Pod is launched, with actuation triggered by a SpaceX engineer working in conjunction with the Pod team. For teams utilizing the umbilical, no structure can be mounted above the NAP, as that would block umbilical access.

The NAP's power-out interface is a D-Sub-50 connector. The power available from SpaceX to the D-Sub-50 will be 240 VAC at up to 50 A (single phase, 60 hz). However, since the power routing is 1-to-1 from tube exterior to NAP power-out interface, teams can provide any power they would like.

To make this clearer, see the diagram on the following page for more detail. The Tube Support rack will have several power jacks (female connectors), both for 240 VAC and 110 VAC. There will be a single D-Sub 50 connector ("Tube Power") which is wired 1-to-1 through the rack, tube, umbilical, and NAP.

For providing 240 VAC to the Pods, SpaceX will implement an external patch cable connecting the 240VAC jack to the Tube Power connector. If teams wish to provide their own power, they can remove this patch cable and provide any power source they would like, as long as per-pin current is limited to 2.5 A and total amperage is less than 50 A.

Tube Support Rack and Hyperloop Power Umbilical Wiring



6 COMMUNICATIONS

Connectivity to the Pod will occur via an Ethernet network bridged between the Staging Area and the Pod itself. SpaceX will provide all infrastructure for this bridge network and will use a radiating cable mounted along the top for the length of the tube. Teams will interface with this infrastructure from the Staging Area and directly on their Pod.

- Bandwidth to the Pod will vary but expected bandwidth requirements should not exceed 20Mbps.
- Network latency between the Pod and staging area is expected to remain <10ms.
- Network access to the Pod is expected to remain continuous while the vehicle is in the staging area or in the tube. In the event of the loss of network connectivity, the Pod should enter a safe state.
- Team equipment will only be allowed on this network when they are the primary team on the track. This is intended to prevent interference between teams.
- Teams using their own communication systems outside of the tube shall not overlap with 802.11g Channel 11 (2462MHz).

IP Addressing

Teams are allocated a static 8 bit subnet 192.168.1.0/24. Teams may allocate IP addresses in this subnet as they like. There will be no DHCP or DNS servers on this network. There will be no external network access on this network. Teams shall not bridge this network or provide remote access to this network.

Staging Area Network Access

An Ethernet 15 port switch will be present at both the ingress and egress staging areas. These two network switches will be the only network access points to the Pod. Teams may determine how to allocate these ports.

Pod Network Access

A 9.5” x 8” x 1.5” (LxWxH) Network Access Panel (NAP) will be provided to teams in the staging area with all necessary network bridge equipment. Teams are to mount the NAP perpendicular to the track surface with the panel facing to the rear of the Pod. There should be no metallic obstructions above or to the rear of where this panel is mounted on the vehicle. Teams should provide 1/4-20 mounting holes in locations shown on the network access panel drawing. A 0.25-inch clearance is expected below the NAP and it cannot be located below the Propulsion Pusher Interface (if utilized). The NAP will weigh approximately 3 pounds. If the NAP will be encapsulated for aerodynamic or other purposes, a material such as fiberglass should be used with low RF propagation loss at 900 MHz and 2.4 GHz frequencies. Materials such as carbon fiber will likely attenuate the signal sufficiently to interfere with communications and therefore should not be used to encapsulate the NAP.

The panel will have a DB9 Male bulkhead connector for power. The Pod should provide a 9-36VDC source to the panel (Pin 5 for ground; Pin 9 for power), which will draw 20 W. The panel will also have a RJ45 Ethernet socket teams are expected to plug their Pod network into.

The DB50 connector is an optional auxiliary power connector (see Power section).

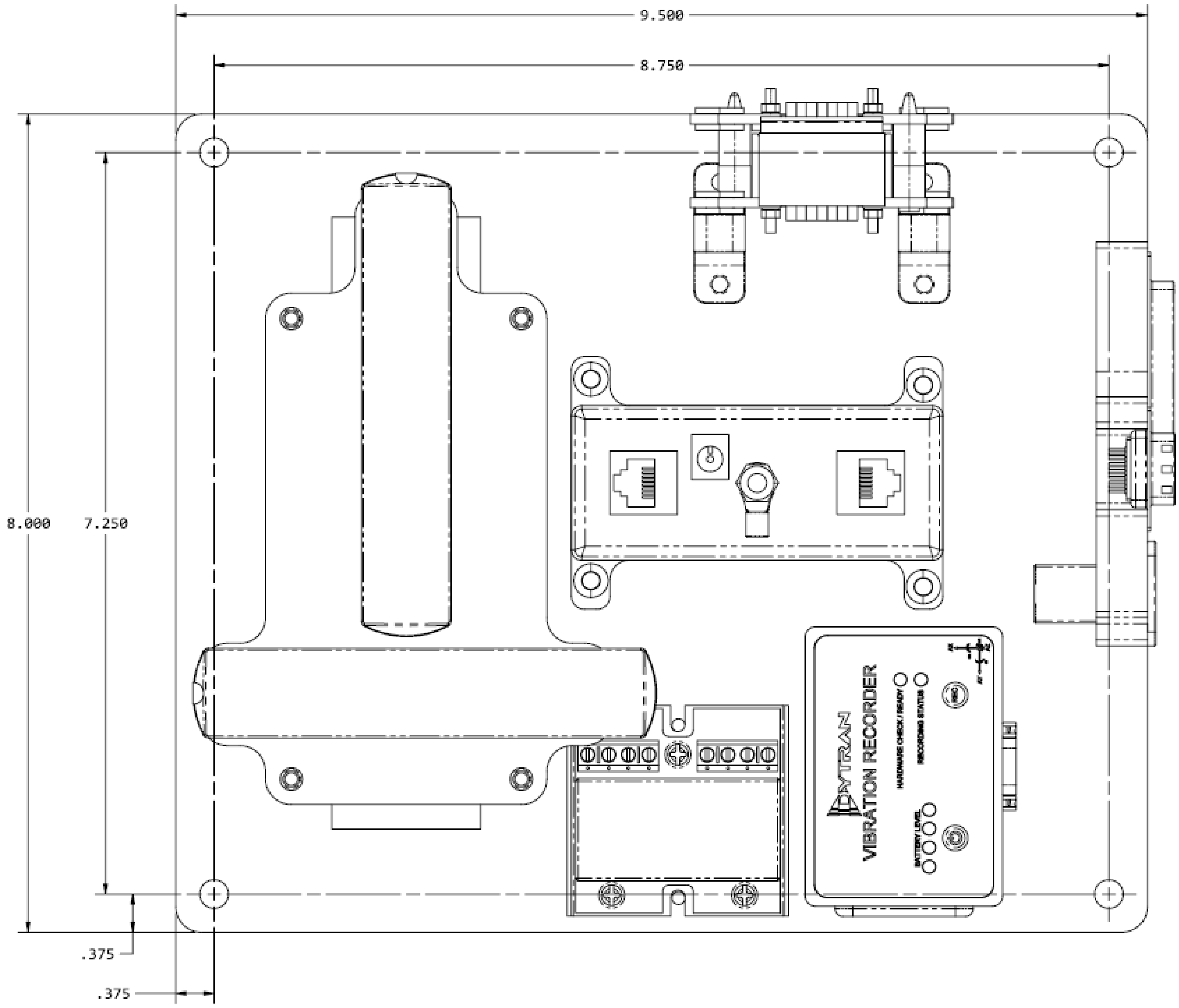
Alternative NAP mounting

A NAP mounted as recommended will contain antennas in the proper mounting configuration for working communications. However, this may not work well for all Pods, so teams can choose to use the NAP as provided, but purchase and mount their own remote antennas. A NAP will still be used, but the antenna to modem connections (2x RP-SMA) can be undone by the team so their remote antennas can be attached instead.

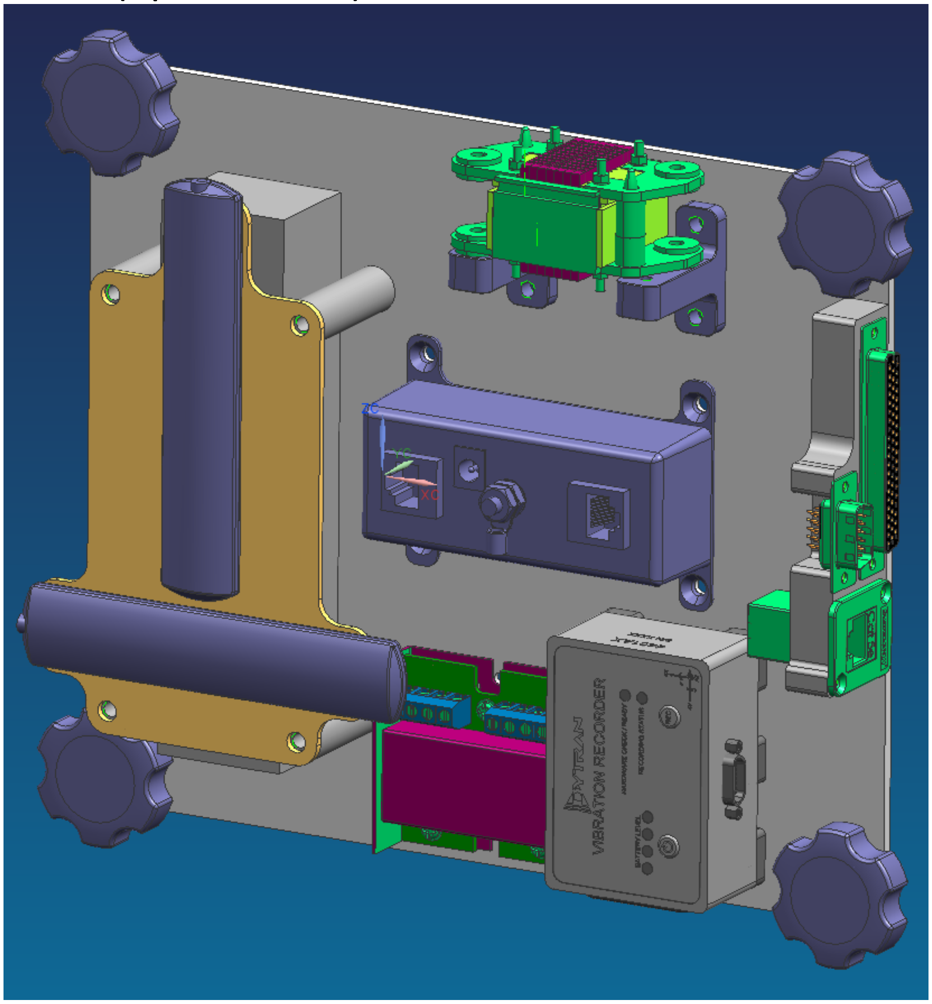
In this case, as long the Pod doesn't need to use the Hyperloop Power Umbilical (see Section 5), the NAP can be placed anywhere,

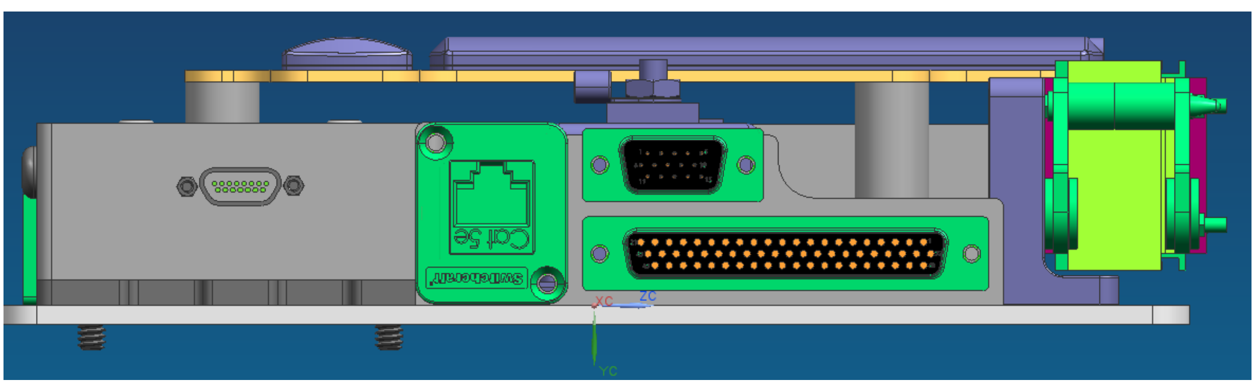
The only approved antenna is this wave blade antenna: http://www.l-com.com/wireless-antenna-900mhz-to-25ghz-multi-band-2dbi-1-4-wave-blade-antenna. Note that Pods must mount two of these remote antennas. The remote antennas should be mounted with the broad side of the antenna facing up, with no conductive material blocking the path to the top of the tube. The orientation of the two antennas should be different to improve link quality, such as 90 or 180 degrees apart.

Network Access Panel (mechanical drawing)

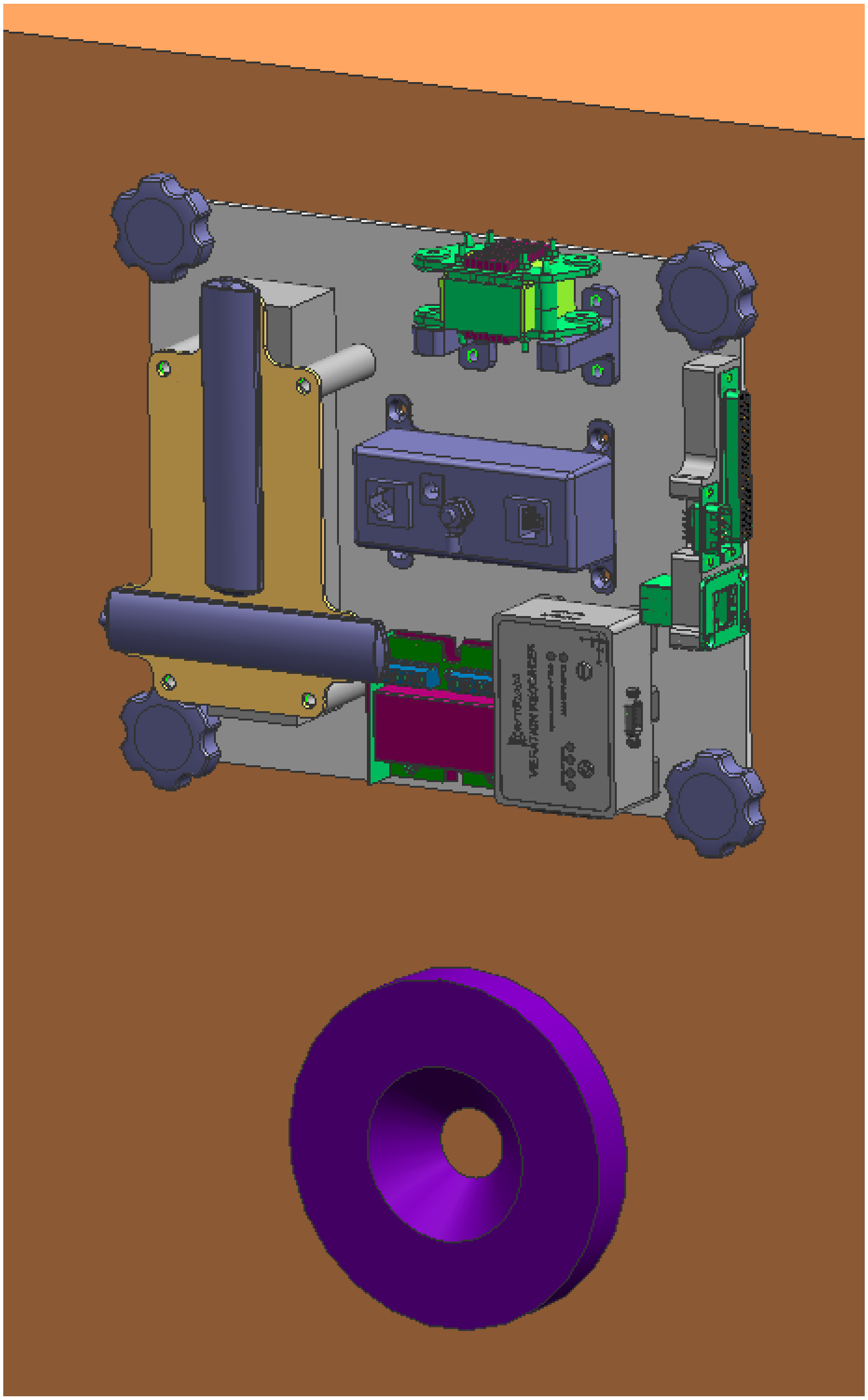


Network Access Panel (top and side views)





Sample mounting of NAP at aft end of Pod. Optional Pod Receiver Interface is shown below the NAP. If a Pod is using the SpaceX Pusher, sufficient space must be left to support the Pod Propulsion and Receiver Interfaces (see Section 3; older version of PRI shown in image below).



7 NAVIGATION AIDS

Every 100 feet, a 4-inch wide reflective circumferential stripe will be applied to the inner circumference of the tube. The stripes will be located on the upper 240° of the tube ("8 PM to 4 PM"). The stripe material will consist of Reflective Tape in Fluorescent Red-Orange Color. Tape of this width is not readily available in small quantities, so it is recommended that teams "double up" on 2-inch tape if they wish to do in-house testing.

At 1,000 feet, a pattern of ten 4-inch wide stripes separated by 4-inch "blank sections" of the underlying steel tube will be applied as a "1,000 feet left" marker for the Pods. The entire installation is thus 76 inches long.

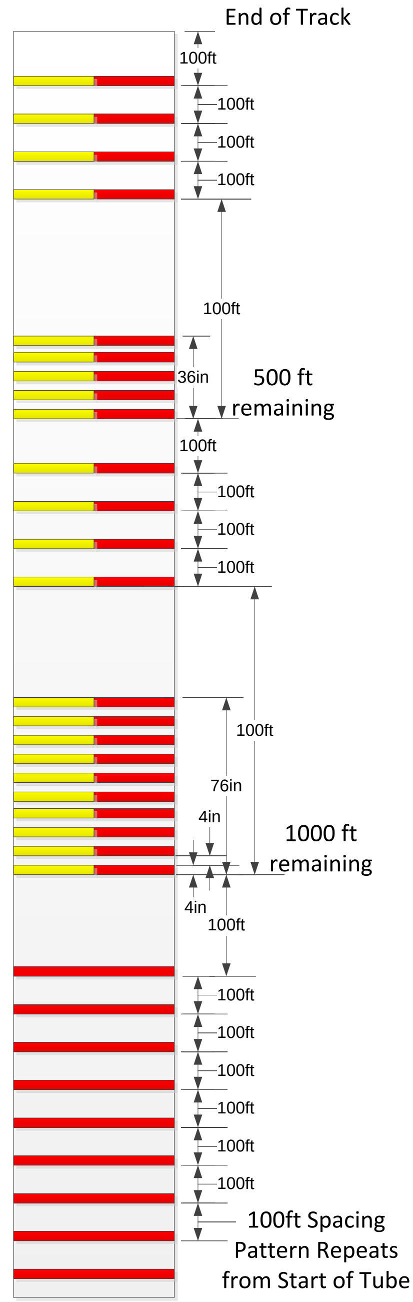
Similarly, at 500 feet from the end of the tube, a pattern of five 4-inch wide stripes separated by 4-inch "blank sections" of the underlying steel tube will be applied as a "500 feet left" marker for the Pods. The entire installation is thus 36 inches long.

Please note that there will be discontinuities in the tape in the upper 45° ("11:15 PM to 12:45 PM") due to tube utilities.

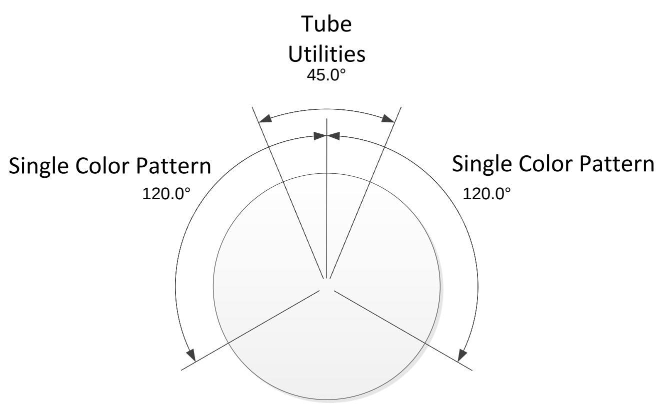
The entire interior of tube will be illuminated throughout at standard room levels using standard "white" floodlighting from directly above the track. Full lighting specifications (and reflectivity data for the steel) will be released later.

See next page for depiction of optical markings.

Summary of Optical Markings



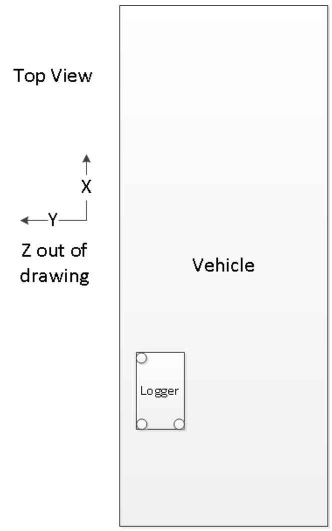
Overhead view of navigation markings
Vehicle velocity vector moving up
(not to scale)



Tube Cross Section
Vehicle velocity vector into drawing

8 ENVIRONMENTS

SpaceX will provide a self-contained environments measurement system to be used for measuring the dynamics environment, temperature and pressure. The currently baselined logger is the Mide Slam Stick X Aluminum. A 3D model for the Aluminum version of the logger is available on the product website. It is possible that the logger type is changed later in the process. Teams should make sure they can accommodate a logger with dimensions no greater than 3” in length, 2” in width, and 1” in height.



Concept of Operations

1. SpaceX official installs activated logger on test vehicle in the Ingress Staging Area of the track.
2. Test is performed.
3. SpaceX official uninstalls logger in the Egress Exit Area portion of the track
4. SpaceX official extracts logged content and stores with other test artifact files.

Installation

Teams will provide a logger mount point on the chassis of their vehicle. The mount point shall consist of three holes threaded for a 4-40 bolt. The holes must be at least a ¼ inch deep. The logger bolts shall be torqued to 6in-lbs. The logger shall be aligned with the X axis pointing out the front of the vehicle within 10° of the nominal direction of travel, parallel to the track. The Y axis shall point out the port side of the vehicle, the Z axis out the top of the vehicle. The plane formed by the X and Y axis must be parallel to the plane of the track within 5° at all times. This mount point may not be isolated from the chassis in any way that would alter the acceleration measured at the logger when compared to the acceleration experienced by the chassis. The mounting location on the vehicle shall be accessible while the vehicle is in the Ingress Staging Area of the track for an operator to use a torque wrench to install the logger.

Data Availability

Logged test data is available to teams for their vehicle by request.

9 SUPPORT INFRASTRUCTURE

Pod Vacuum Chamber

Before being placed in the Hyperloop, Pods will have to demonstrate vacuum compatibility. To do so, SpaceX will provide a full-scale vacuum chamber. The chamber will have the same diameter and subtrack alignment as the Hyperloop, except its length will be greatly diminished.

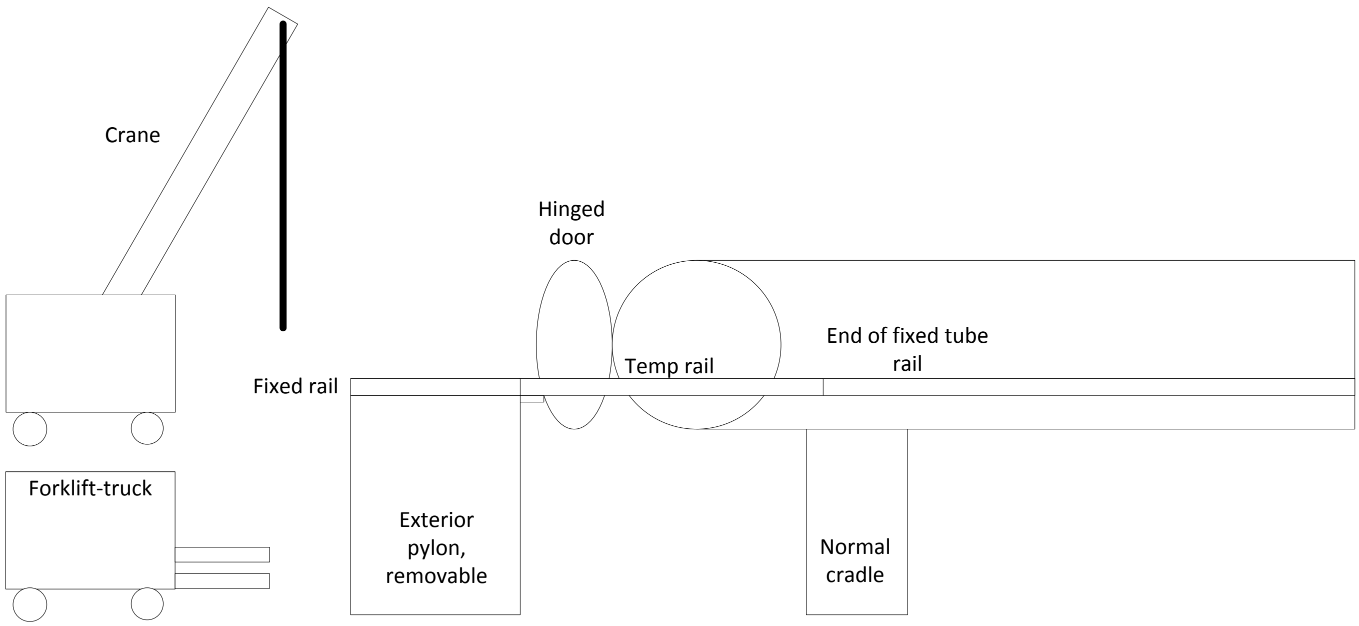
The vacuum chamber will have a subset of the optical markings described in Section 7 for sensor tests.

Pod External Subtrack

Before being placed in the Hyperloop, Pods will have to demonstrate basic low-speed motion (determined on a case-by-case basis, but hovering and braking are likely demonstrations). To do so, SpaceX shall provide an external full-scale aluminum subtrack (the aluminum plate and rail).

Staging Area (Loading) and Exit Area (Unloading)

The Staging Area will be a 20-foot long concrete pylon with the aluminum subtrack mounted on top. Pods will be loaded by placing a concrete pylon with fixed rail near the entry, with a temporary rail segment added to span the gap. Thus, when Gate 1 is open and the exterior concrete pylon is in place, there will be a continuous subtrack from the Staging Area into the Hyperloop. A crane and forklift will be available for loading onto the rail. The Exit Area (for unloading) is identical to the Staging Area and a separate crane and forklift will be available.



10 POD SAFETY GUIDELINES

Pod Safety Guidelines

The following are all Pod safety guidelines (not requirements). In cases where Pods do not comply with the guideline, the teams will have to prove an equivalent and reasonable level of safety. As an example, if a Pod discharges its batteries at a rate greater than the manufacturer's specification, the team must explain, in detail, why their selected discharge rate is safe. SpaceX, at its discretion, will deem whether the alternative implementation is acceptable.

1. All Pods shall maintain structural factors of safety of at least 2.0 for reasonable loads cases (e.g. acceleration, deceleration, pressure, etc.)
2. Battery discharge rates shall be within the manufacturers specification
3. Fusing elements shall be designed for vacuum applications or be characterized in the expected environment with the worst case maximum voltage and inductance
4. The battery management system shall be fault tolerant to preventing overcharging the cells
5. The battery management system shall isolate the battery in over temperature conditions
6. All compressed gas shall be limited to pressures of 4,000 psi
7. All high pressure gas systems shall have vent and relief valves
8. Flow directions through vent and relief valves shall be oriented for the safest possible outcome
9. Pressure vessels shall comply with applicable sections of the ASME boiler and pressure vessel code
10. Teams shall not cause subtrack plates to increase in temperature by more than 30°C. For magnetic systems, this will help determine maximum allowable stationary hovering durations.
11. Braking systems shall be redundant
12. Cryogenic liquids shall not be used
13. Pod designs shall be compatible with the subtrack structural tolerances given in this document