SpaceX Hyperloop Test-Track Specification

Revision 1.0

October 20, 2015

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 Summer 2016, 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 or can be posted on the Hyperloop Forum at http://tx.ag/hyperloopforum (click on “Enroll Now” to join).

2 STRUCTURAL

The test track will be an approximately 1-mile-long steel tube with a 6-foot outer diameter, fitted with an aluminum sub-track and rail mounted to a concrete fill bed. At the tube's egress door, there is a 12-foot-long "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: 1 mile (approximate)
- Subtrack material: Aluminum 6101-T61
- Subtrack roughness: 125 RMS with potential for occasional surface scratches up to 0.008"
- Subtrack thickness: 1.0" for first and last 200 feet; 0.5" for remainder of tube
- Rail Material: Aluminum 6061-T6
- Internal Pressure: 0.02 – 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 the range given above.

All critical dimensions and tolerances are outlined on the drawing on the next page. Please note that the latest drawing revision will always supersede notes in this specification. These notes below are for reference only.

- 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.

Four important open items to be decided after Design Weekend:

- SpaceX is attempting to widen the subtrack from 12" to 15" in order to give teams larger levitation surfaces. However, that widening is not definitive and thus, two drawings are shown.
- SpaceX has not decided the final flushness of the aluminum to the concrete. In the drawings, it is shown as flush, but it might be elevated as high as resting on the concrete.
- SpaceX is still 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 get the gap size down to 0.05" for the first several hundred feet of the track. Gaps may

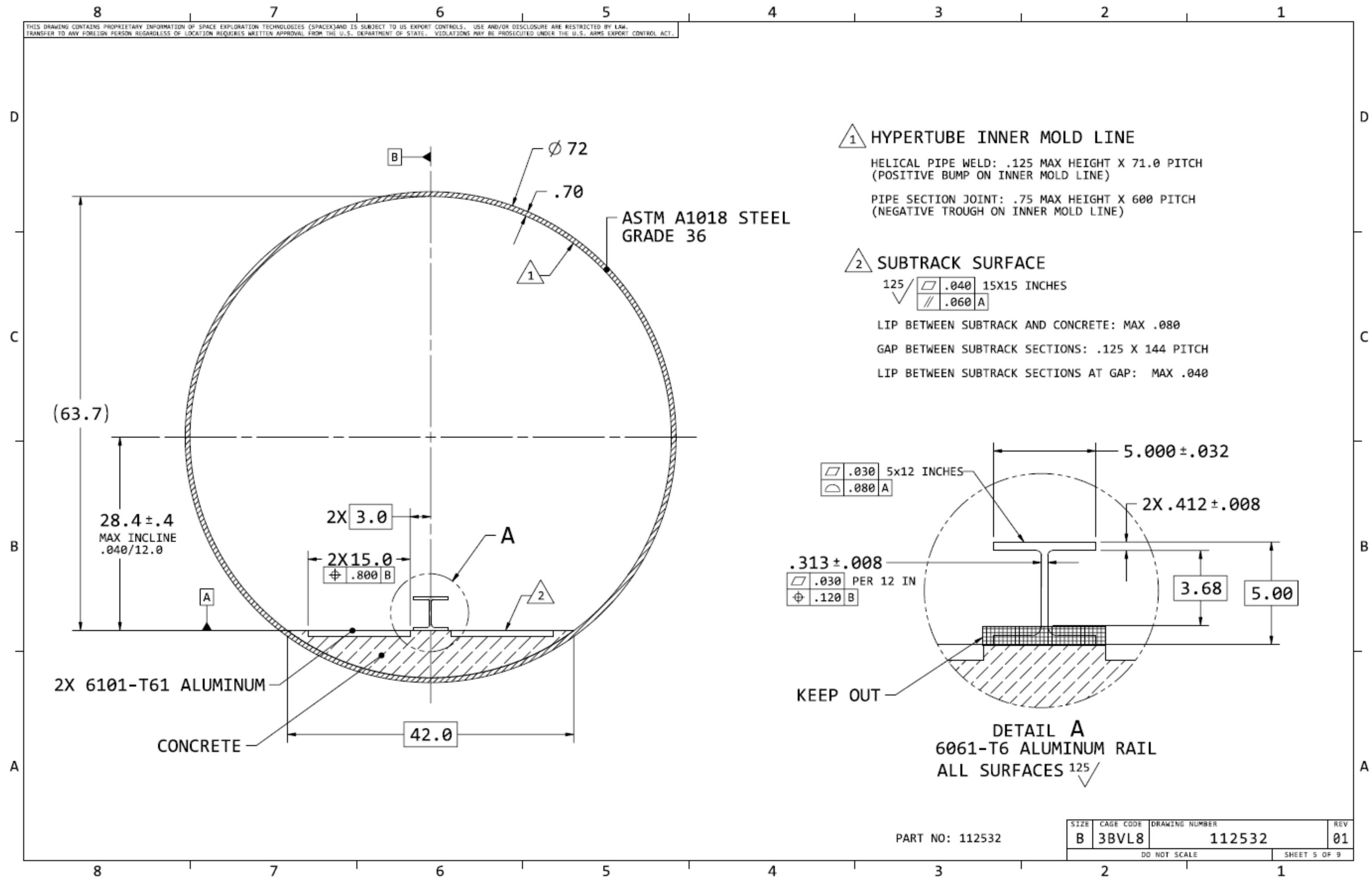
or may not be filled with a non-conductive flexible filler. Maximum steps in height between plates on the track will be limited to 0.04” or less.

- The shape of the central rail is baselined as an I-Beam shape, but see note on Page 7.

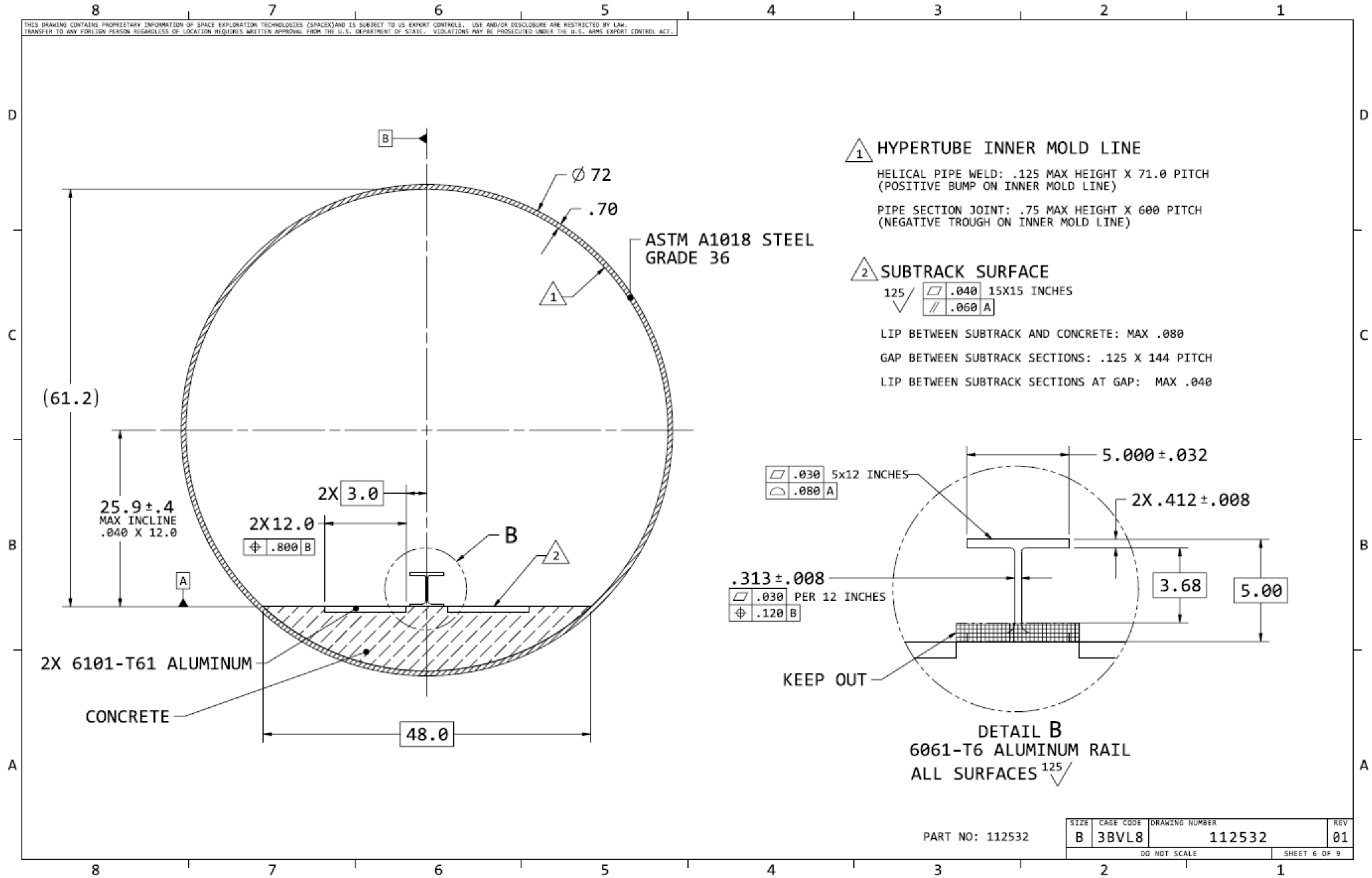
The test track has been designed to be flexible and to allow competitors to implement, at a minimum, the following three types of levitation/suspension:

1. Wheels: The concrete (and aluminum) flat sections 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.

Subtrack: Aluminum subtrack (30” total surface width) with central rail (all dimensions in inches)

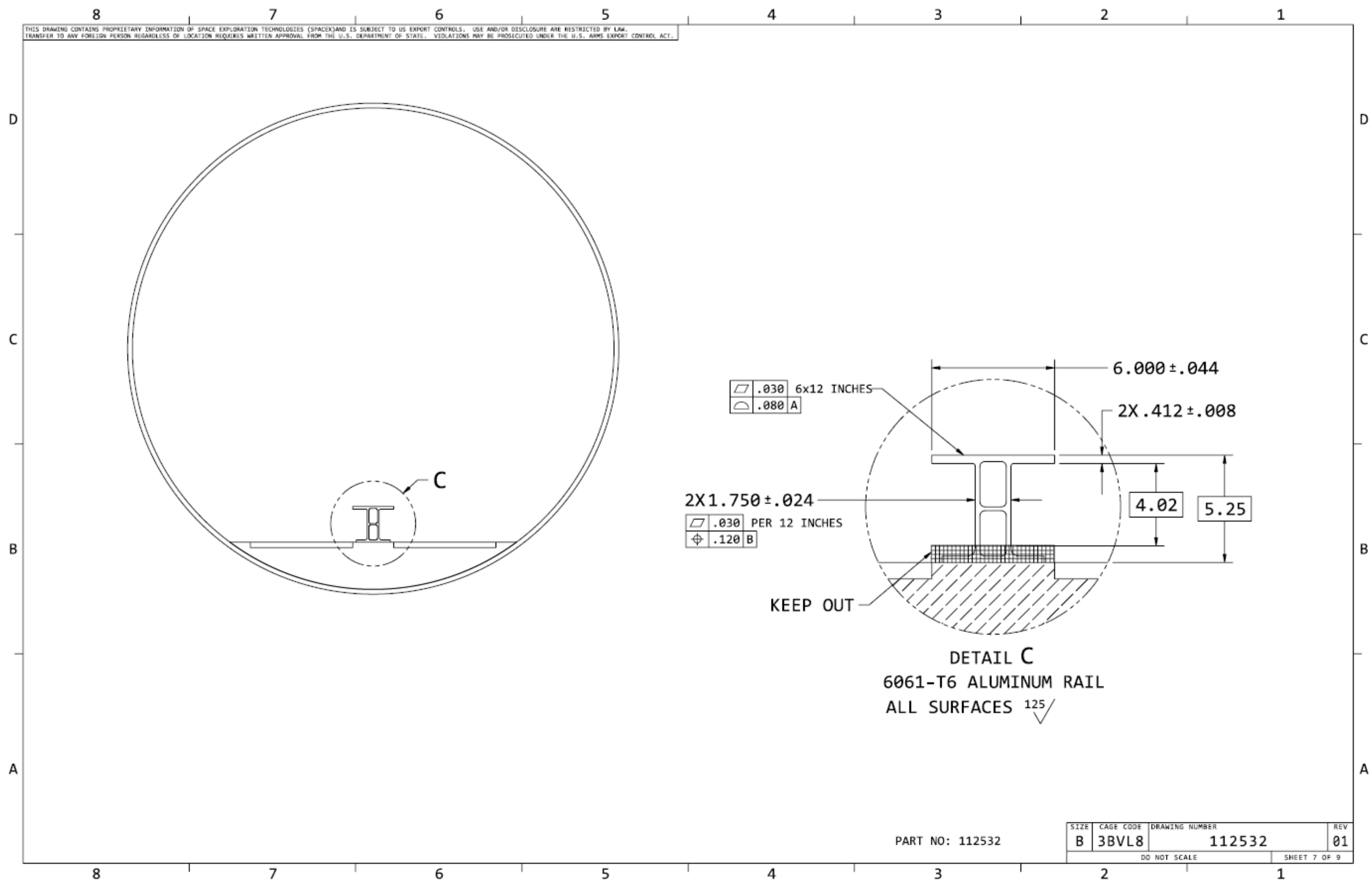


Subtrack: Aluminum subtrack (24” total surface width) with central rail (all dimensions in inches)



Potential Alternative Central Rail

The baselined central rail is currently an I-beam shape, but SpaceX is considering a custom rail shape to give teams more flexibility and surface area. This alternative rail detail “C” would directly replace the rail detail “A” or “B” in the previous specifications of the drawing.



3 PROPULSION SYSTEM AND INTERFACE

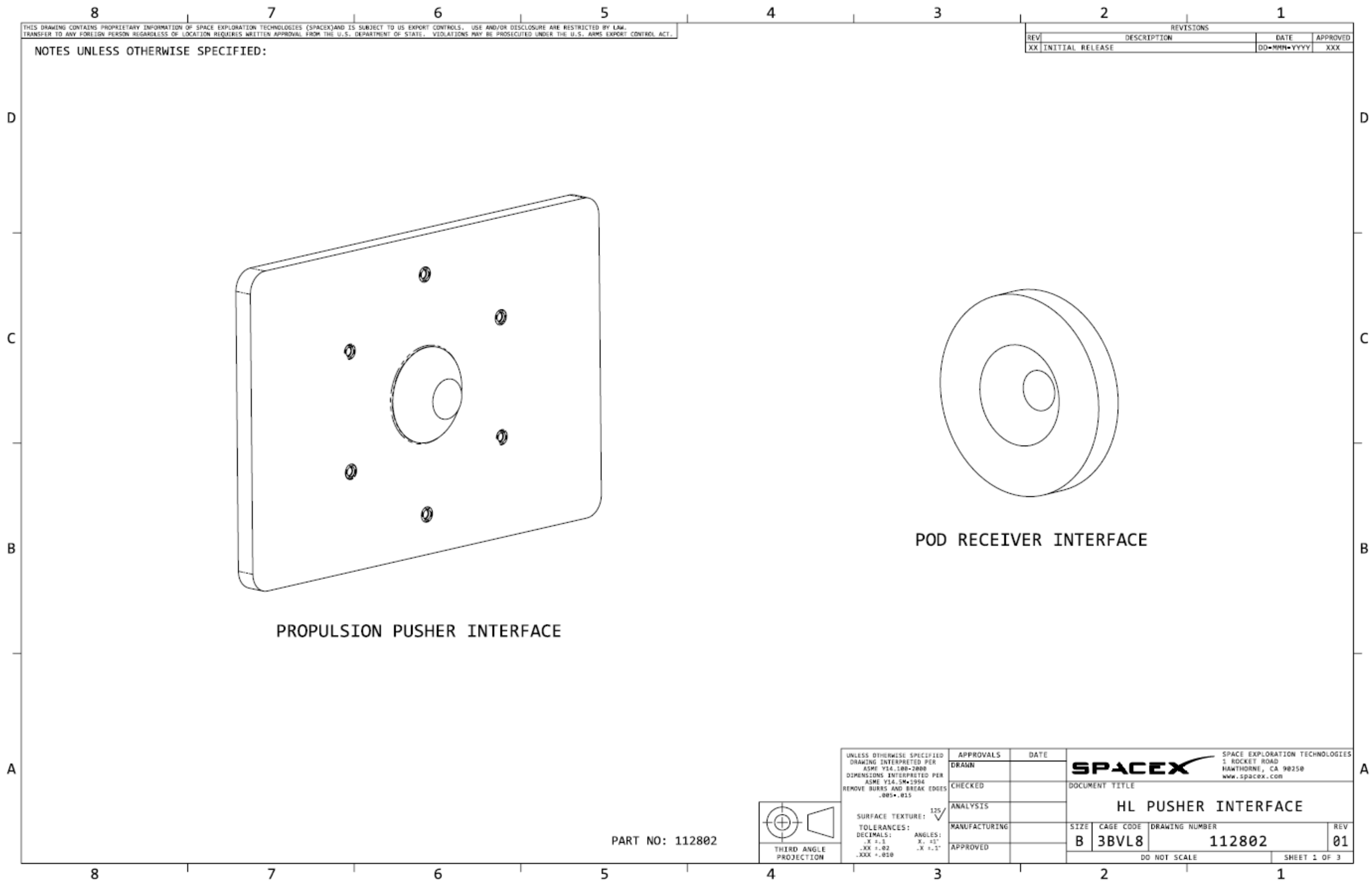
The test track will not be fitted with a structurally integrated propulsion system. Instead, teams have 3 options with regards to initial propulsion:

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. This option only applies to very 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 consists of a flat pusher plate with a centering cone, which will be laterally centered in the tube. See diagrams on the next three pages.
    b. The height of the cone center can be adjusted, in 2.0-inch increments, between 8 and 20 inches above the concrete, as specified by each Pod team.
    c. The Interface will float up to 1.0-inch vertically to accommodate levitation after contact.
    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 lbs, 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 800 feet.
    f. Each Pod acceleration profile will have 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 very likely that Pods are started at lower values of acceleration 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.

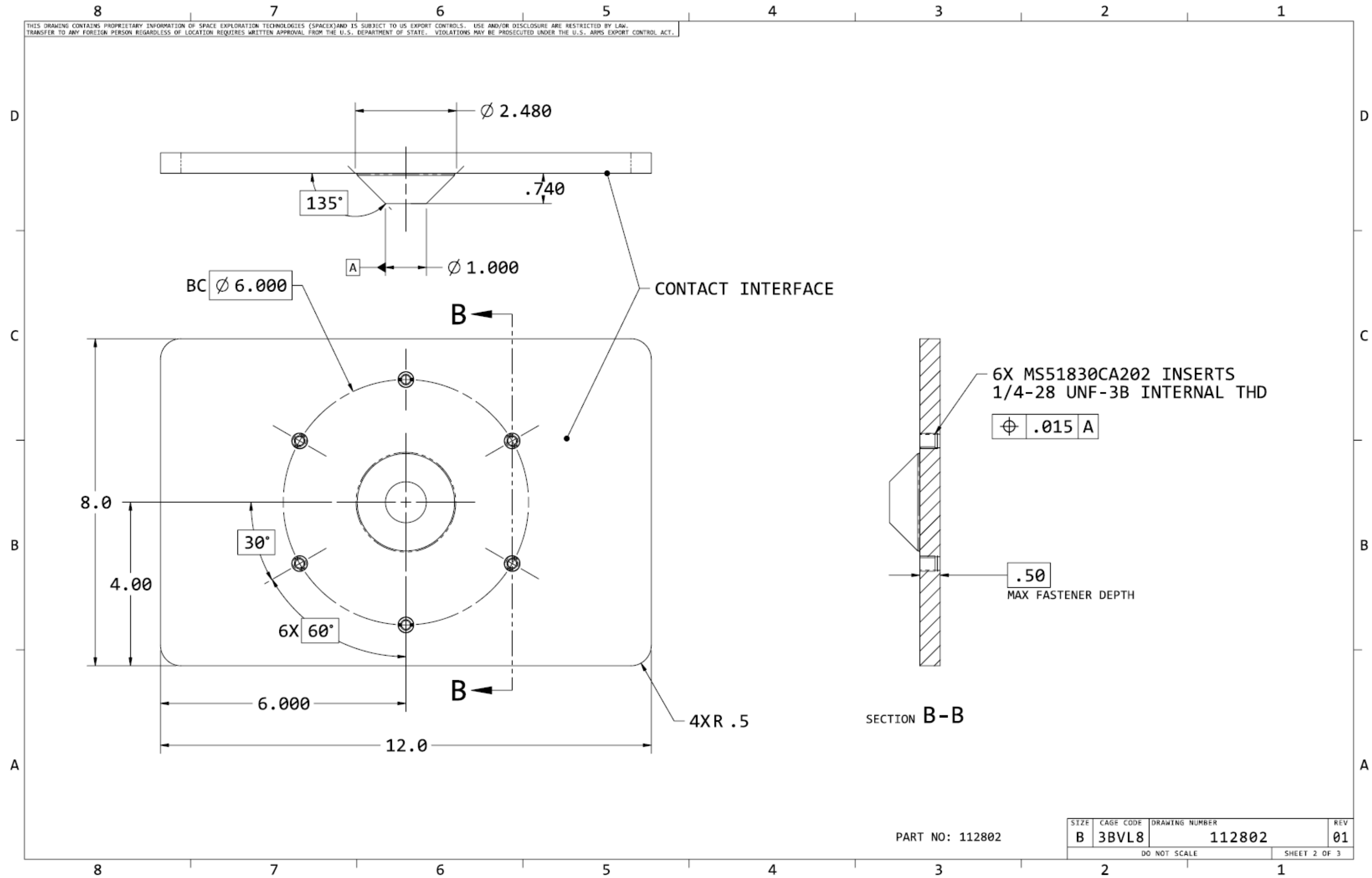
Representative pusher acceleration values

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

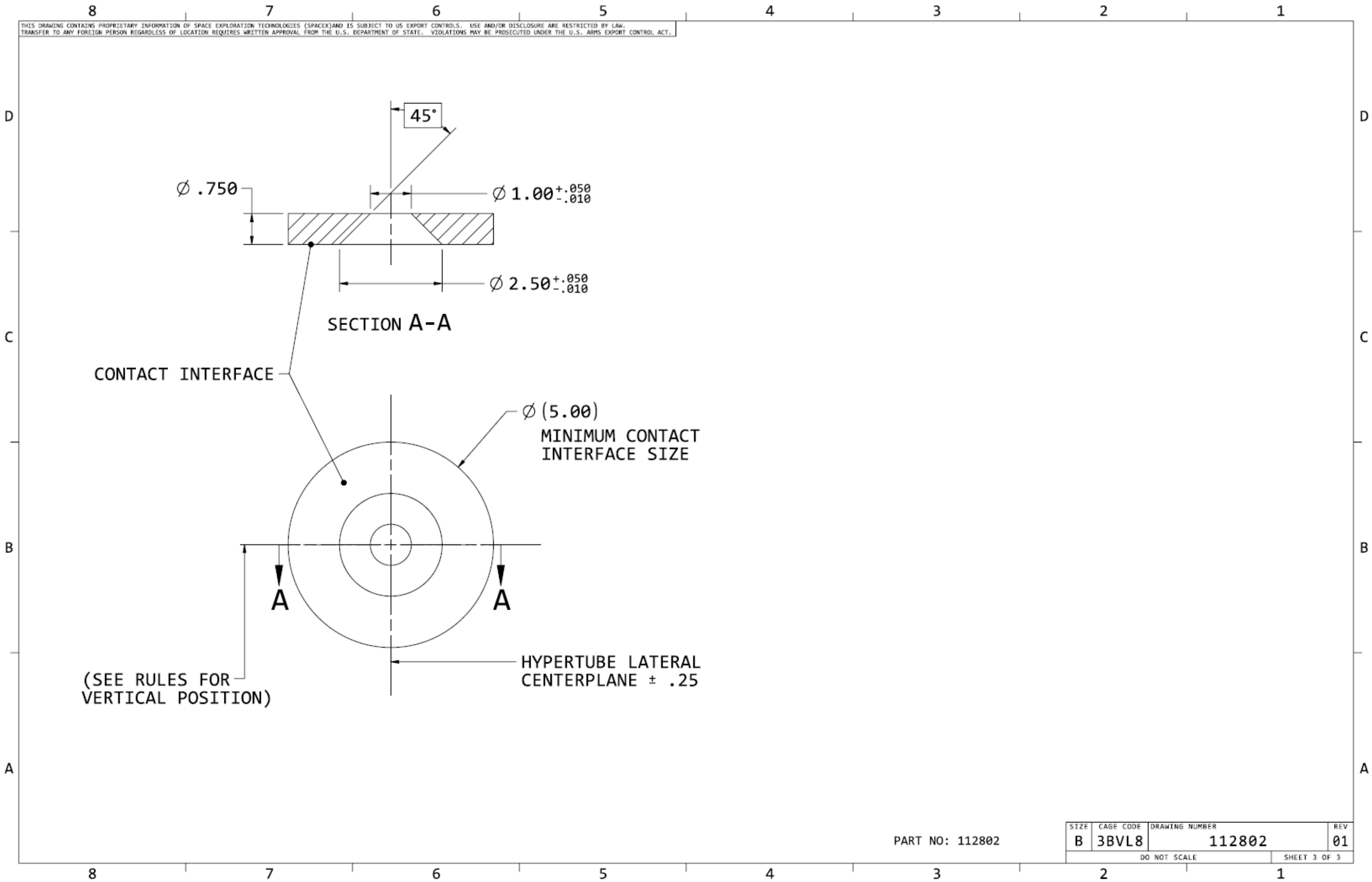
Pusher Interface (1 of 3) (all dimensions in inches)



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



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



4 POWER

In general, Pod power shall be provided on the Pod itself and there is no auxiliary electric rail in the test track. However, for the pre-launch phases, SpaceX will provide a quick-disconnect electrical umbilical, known as the Hyperloop Power Umbilical. It will be a standard electrical connector with a lanyard release mechanism. The specific capacities and connector-type for the power provided will be released after subsequent feedback is received from teams building Pods for Competition Weekend. Reasonable supplies would be:

- 240 VAC at up to 60 A (single phase, 60 hz)
- 110 VAC at up to 60 A (single phase, 60 hz)
- 28 VDC at up to 100 A

5 COMMUNICATIONS

SpaceX will provide four Access Points (AP’s):

1. External to the tube at the entrance (AP_EXT_ENTER)
2. Internal to the tube at the entrance (AP_INT_ENTER)
3. External to the tube at the exit (AP_EXT_EXIT)
4. Internal to the tube at the exit (AP_INT_EXIT)

The external AP’s are meant for connections by the ground support teams or any auxiliary Pod testing. The internal AP’s will be fitted with directional antennas to beam the signal the length of the tube in order to support standard WiFi receive hardware.

The client (Pod) side WiFi requirements are:

- Support either or both 2.4/5 GHz bands (dual band client)
- WPA2/AES capable client
- PSK authentication
- SSID will be determined by SpaceX and communicated to Pod team before Competition
- Supports either static or DHCP (IP/Subnet will be provided Prior to Competition)
- Flat network (i.e. one subnet)

For transmit connectivity, Pod teams may select any method/hardware they would like. A known solution is to install an AP on the Pod itself; as an example, while large, the Cisco IW3700 would meet the necessary power levels.

Roaming between wireless access points mid-flight (i.e. from AP_INT_ENTER to AP_INT_EXIT) will be allowed, but the specifics will have to be discussed with the SpaceX team.

6 NAVIGATION AIDS

Every 100 feet, a 2-inch wide reflective circumferential stripe will be applied to the inner circumference of the tube. The stripes will be located on the upper 180° of the tube ("9 PM to 3 PM"). The stripe material will consist of Reflective Tape in Fluorescent Red-Orange Color (P/N 75050060534).

At 1,000 feet from the end of the tube, the upper 180° of the tube will be split into two 90° sections. The right side of the tube will continue to use the same Fluorescent Red-Orange tape. The left side of the tube will use Reflective Fluorescent Lime-Yellow tape (P/N 75050060518) for the remainder of the tube. The pattern on both sides of the tube will be the same, color will be the only difference.

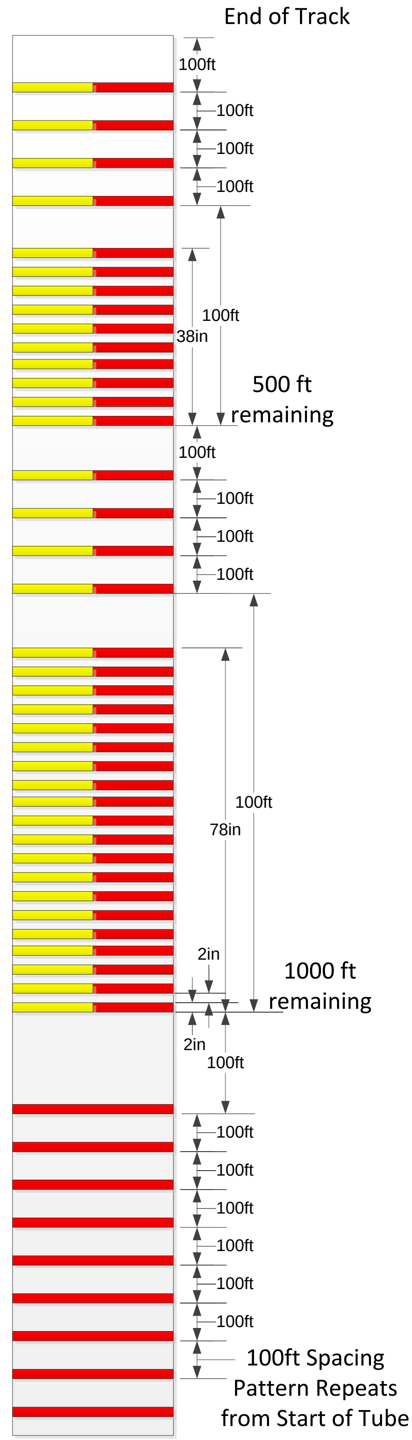
At 1,000 feet, a pattern of twenty 2-inch wide stripes separated by 2-inch "blank sections" of the underlying steel tube will be applied as a "1,000 feet left" marker for the Pods. The entire installation is thus 78 inches long.

Similarly, at 500 feet from the end of the tube, a pattern of ten 2-inch wide stripes separated by 2-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 38 inches long.

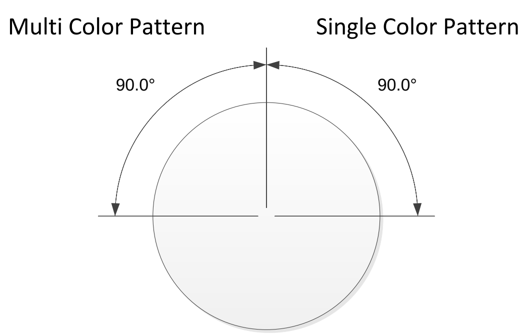
The entire interior of tube will be illuminated throughout at standard room levels using standard "white" floodlighting from directly above the track. Based on Design Weekend feedback, it is possible that this is changed to narrow-band illumination. Soon after Design Weekend, full lighting specifications (and reflectivity data for the steel) will be released.

See next page for depiction of optical markings.

Summary of Optical Markings



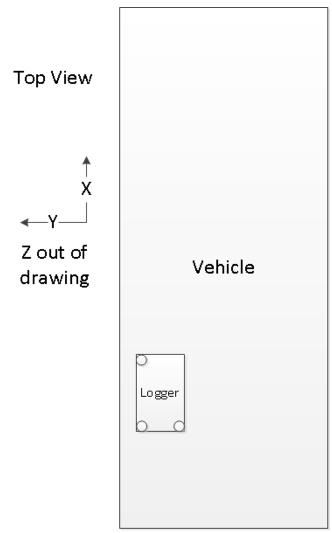
Overhead view of navigation markings
Vehicle velocity vector moving up
(not to scale)



Tube Cross Section
Vehicle velocity vector into drawing

7 ENVIRONMENTS

SpaceX will provide a self-contained environments measurement system to be used for measuring the dynamics environment, temperature and pressure. The logger to be used is the Mide Slam Stick X Aluminum. A 3D model for the Aluminum version of the logger is available on the product website.



7.1 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.

7.2 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.

7.3 Data Availability

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