Complex Hyperloop Capsule Safety Requirements and Risk Mitigations

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Abstract

Hyperloop, a 5th mode of transportation, was promoted worldwide in August 2013 by a White Paper released on the internet by Elon Musk (Contributors, 2013). Hyperloop Transportation Technologies (HTT) was the first company to announce it was taking the idea “from concept to funding” (Insider, 2016) (Kudarauskas, 2007) (Wikipedia, 2018) The technologies used in the Hyperloop are not new, but they are combined in a new manner and thus present new safety challenges. Beyond safe operations the most vitally important challenge is passenger safety within the capsule. Due to capsule operation inside of a low pressure tube (~ 1/1000 atmosphere), speeds approaching Mach 1 and life support requirements similar to those of space travel, there are special hazard mitigations which must be developed. This paper describes capsule hazards and mitigations along with specialized evacuation processes appropriate for this new form of specialized transportation.

Introduction and System Overview

Hyperloop™ is a technically advanced transportation system that has the operational structure to be unparalleled in safety. The Hyperloop™ tube creates an enclosure that is immune to weather, disturbance from outside events and concerns about crossing traffic. The lack of “at grade” intersections also allows safe crossing for vehicles, pedestrians, bicycles and wildlife, which is not possible with today’s land based systems. Capsules travel only one direction during operation thus there is nil chance of frontal collisions. Digital control and communication allow instantaneous reporting of capsule position, speed and status. These physical and control system advantages are clearly bringing us to the conclusion that this new mode of transportation has the potential to surpass anything the planet has ever seen in terms of safety, reliability, scheduling and comfort. However, there are also obvious challenges associated with this new technology, due to high capsule speeds in a confined space, moving in an operating environment that is at low vacuum, and including a passenger cabin that needs self-contained life support. The Hyperloop Transportation Technologies (HTT) safety team, comprised of doctors, engineers and highly experienced safety experts has developed strategies to mitigate and reduce the risks associated with those unique operating conditions. This paper describes Hyperloop’s risks in more detail and proposes mitigating solutions focused primarily on capsule and passenger requirements found in rail and aerospace standards.

The Hyperloop is simply a transportation system which moves passenger capsules at high speeds inside of evacuated tubes. The concept was first proposed by Robert Goddard in 1904 as the Vactrain which has had numerous champions over the years including scientific articles in the 1970’s by Robert M. Salter of the Rand Institute (Salter, 1972), and most recently a Swissmetro project in the late 1990’s and early 2000’s (Blog, 2013). The idea catapulted to worldwide interest after the publishing of a 2013 White Paper by a group of Tesla and Space-X engineers and scientists (Contributors, 2017). There are now many groups around the world working in various ways to bring the idea to reality. Hyperloop Transportation Technologies (HTT), a crowd-based effort with engineers and scientist located around the world, and for whom the authors of this paper are contributors, is constructing two full scale prototypes in Toulouse, France. The Hyperloop system (Figure 1) is a purely electrical propelled mode of transportation which takes advantage of the significant reduction in drag due to the low tube pressure and also
benefits from major improvements in solar panel efficiency and linear motor control. The imperative created by an overburdened transportation system, gridlocked cities and the need for improved efficiency and safety has propelled this technology to the edge of commercialization. What is left is to test and optimize the system, integrate the numerous technologies and create a certifiably safe system with tubes connecting cities ideally no more than 1000 km apart. This paper is mainly focused on the safety aspects of capsule operations including life-support, losses of capsule pressure, emergency evacuations and other challenges of operating within a near space environment.

The following is a description of various capsule operation risks and how they can be overcome or mitigated using solutions taken from high speed rail and aviation standards as well as space vehicle operations. These safety solutions are presented for the general public as well as to inform possible certifying agencies.

**Highest System Risk – Capsule Doors**

We used FMECA (Figure 2) and calculated risk priority numbers to identify which systems have the highest impact on operational safety. The highest risk area from that analysis is leakage of cabin air due to faulty door operation. This is not surprising: the door system is used frequently, has a major impact on system operation, and most importantly for Hyperloop, presents a major risk during failure in the form of reduced cabin pressure and life support. Metro systems around the world experience high door failure rates (Sarin, 2018) and those experienced in metro line safety point to this as one of the two most failure-prone systems in metro transportation. The Risk Priority Number, which is very subjective for new systems, hit 270 on a three input assessment as shown below.

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Causes of Failure</th>
<th>Potential Effect of Failure</th>
<th>Severity</th>
<th>Current design Controls Preventing Fault</th>
<th>Overview</th>
<th>Current Design Control Detection</th>
<th>RPN</th>
<th>Risk Priority Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door Capsule</td>
<td>Critical system failure – Door failure</td>
<td>Loss of pressure in Capsule, Unable to open at station, Injury to passengers</td>
<td>9</td>
<td>Robust door seals that inflate with pressure differential like aircraft, Safety Latch, Routine Inspection and maintenance</td>
<td>5</td>
<td>Capsule telemetry (pressure in capsule and door seal)</td>
<td>5</td>
<td>270</td>
</tr>
</tbody>
</table>

**Figure 2 - Hyperloop System FMECA and Door RPN**

The door of the Hyperloop capsule is complex, much more complex than aircraft, and similar in function to space docking systems but with the advantage of fixed locations for the capsule and station. The primary similarity is the need for a pressure tight seal on both ends of the passage way. The HTT door, and the associated passenger gateway, referred to as a Docklock®, performs several functions which are unique to this form of transportation.
The seals within the capsule door are of utmost importance as any leakage will slowly deplete air within the capsule pressure vessel. The doors and seals need to be robust such that they can operate thousands of times without damage. A capsule has a turnover rate of approximately 3 times per hour. Given a day of 18 working hours, a typical door will perform approximately 108 (54 opens, 54 closes per day) moves per day or 39,420 operations per year. Seals, actuators, sensors, latches, bellows and cleanliness are all items that must be robust and reliable at that success level. The door design is an inside sliding structure and due to a positive pressure differential with the tube aids in pushing it against the fuselage and sealing it against leaks. With wear it can be expected that small leaks around the door seals will be experienced. Small leaks will be countered by adding air from onboard pressurized bottles. The onboard air bottles are currently sized to compensate for larger leaks which will be addressed later. Even for long trips, due to these air reserves, the hazard of a door leak is an exceptionally low risk to passenger safety.

There are two types of doors on the capsule. The passenger loading doors which connect to the station Docklocks, or alternatively to emergency ports along the route, and a second set of emergency exits which are most similar to aircraft evacuation doors. The emergency doors are sized per Code of Federal Regulations (14.1C Part 25D, §25.807: Emergency Exits) and follow the guidelines for size and location based on capsule capacity. The emergency doors can only be used under conditions that the tube has been repressurized to ambient conditions. Those emergency condition evacuations will be described fully under the evacuation section of this paper.

DockLock® Passenger Gateway and Emergency Exits

The Docklock® is the primary seal against tube vacuum for the capsule door while it is open. It is a pressurized gateway style device that moves from the station wall to the capsule where it seals tightly. The gateway is then pressurized and the doors opened. There is indeed a simpler method to transfer passengers which moves the capsule into an area, such as an airlock, that can be repressurized. However, the added time to repressurize and then evacuate such an air lock chamber, combined with added complexity of isolating that chamber makes it an inefficient method and we deem not an economical solution to transferring passengers quickly. The Docklock® allows passengers and cargo to be loaded quickly while leaving the capsule in a vacuum environment.

The Docklock is also used along the route to provide a primary capsule evacuation point. During an emergency that requires passengers to evacuate the capsule enroute this passage is available at periodic locations. No slides are required as these exit points are located at pylons to which are mounted platforms for escape. This method is preferred and most common as long as the capsule can move safely to the emergency exit point.

In the event of a tube blockage or disabled capsule the secondary evacuation doors are used and the tube must be backfilled to atmospheric pressure prior to evacuations. The secondary doors meet the requirements of the previously cited federal standard and allow passengers to disembark the disabled capsule and proceed in the air filled tube to secondary tube exit ports. The secondary exit ports are spaced much more frequently per regional train tunnel evacuation requirements and allows passengers to exit onto a platform located at the tube pylon.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Speed (mph)</th>
<th>Braking G force</th>
<th>Pax alert time (s)</th>
<th>Braking ramp time (s)</th>
<th>Braking ramp rate (m/s²)</th>
<th>Stop Time (s)</th>
<th>Stop distance (m)</th>
<th>Stop separation @ 40k HW (m)</th>
<th>Stopping Clearance to lead Pod (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>760</td>
<td>-1.0</td>
<td>10</td>
<td>4</td>
<td>-2.45 (-0.25G)</td>
<td>46.1</td>
<td>9,533</td>
<td>13,590</td>
<td>4,507</td>
</tr>
<tr>
<td>170</td>
<td>380</td>
<td>-0.6</td>
<td>9</td>
<td>4</td>
<td>-1.47 (-0.15G)</td>
<td>68.0</td>
<td>13,590</td>
<td>13,590</td>
<td>550</td>
</tr>
<tr>
<td>85</td>
<td>190</td>
<td>-0.6</td>
<td>9</td>
<td>4</td>
<td>-1.47 (-0.15G)</td>
<td>39.4</td>
<td>4,094</td>
<td>6,795</td>
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</tr>
<tr>
<td>45</td>
<td>100</td>
<td>-1.0</td>
<td>10</td>
<td>4</td>
<td>-2.45 (-0.25G)</td>
<td>20.2</td>
<td>1,081</td>
<td>3,398</td>
<td>2,317</td>
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<tr>
<td></td>
<td></td>
<td>-0.6</td>
<td>9</td>
<td>4</td>
<td>-1.47 (-0.15G)</td>
<td>25</td>
<td>1,302</td>
<td>3,398</td>
<td>2,036</td>
</tr>
</tbody>
</table>

Figure 3 - Capsule Braking Distances Vs G Force
Time is of most critical value during any evacuation. From the second that an emergency is state is identified the evacuation time is related to the interaction of capsule speed, braking force, capsule position relative to exit points, and time to extend the Docklock (primary evacuation) or repressurize the tube (secondary evacuation). This chart (Figure 3) shows the interactions between speed, stop times (braking plus alert times), and total stopping distance based on 2 levels of emergency braking forces of -0.6 and -1.0 G. The capsule stopping distance must be less than the separation distance and is shown to be safe under shown conditions. Included is a passenger alert time, plus a ramp in braking forces to create an extended stopping time for passenger comfort. In summary, the emergency brake sequence includes a generous passenger alert time coupled with a smooth 4 second ramp to the full braking force.

**Safe Capsule Environment – Cabin Life Support**

Maintaining proper balance of oxygen, carbon dioxide, humidity, and removal of trace contaminants is accomplished through typical environmental control systems (ECS) used primarily in aircraft but with added systems required to monitor and adjust the capsule air without the availability of outside make-up air. The Hyperloop will use onboard supplies as the air density in the tube is not sufficient to provide the same make-up air as used in aircraft. The Hyperloop pod, which operates in a vacuum tight tube system, is similar to a space capsule in that it must supply its own oxygen, plus include carbon dioxide and carbon monoxide removal systems. This integrated life support system, operating in a self-contained environment, is responsible for maintaining a safe and comfortable cabin per CFR requirements 25.831 et al. This system controls cabin pressure and also removes noxious gases and insures that the vital factors such as O2, CO2, temperature and humidity are always at safe and comfortable levels (Figure 4). Recirculated air will be HEPA filtered prior to reentering the passenger area. The life critical environmental systems shall be redundant such that the failure of one system does not pose a risk to the passengers.

**Capsule Breaches and Loss of Pressure**

As cited at the beginning of this paper the highest risk identified by FMECA is that of a door seal failure. This life critical seal has a safety redundant feature to minimize the risk. But in the unlikely event of catastrophic seal(s) failure the passenger cabin must maintain survivable cabin pressure and oxygen for as long as possible. Two mitigation methods come into action under this failure scenario. The primary method is to release air into the cabin from the onboard pressurized bottles. The bottles are sized (15,000 liters) to maintain a minimum 60kPa (8.8 psi) cabin pressure for three minutes while encountering a leak equivalent to a hole the size of 51.6 cm² (3.14 in²). We have calculated that three minutes of reserve air allows enough time for the capsule to brake to a stop, attach to an emergency Docklock® along the route, and introduce ambient air prior to evacuating passengers. Our design requirement is that the door seal cannot experience a leak greater than 51.6 cm², even under total failure, and thus the evacuation mitigation is always attainable. For smaller leaks, a decision point is required evaluating cabin pressure reduction vs time to destination. Continuing safely to the destination is usually the preferred solution.
A capsule breach is another event that would allow cabin air to leak into the tube vacuum. A breach could occur due to a Foreign Object or Debris (FOD) resting in the tube, likely sitting on the guideway, which could collide with the moving capsule. FOD can originate from items being dislodged from the tube, items potentially separated from a previous capsule or even tools left behind after maintenance. Sloppy or uncontrolled maintenance practices cannot be allowed in this high speed route and special tool procedures are required to prevent any objects left behind that could collide with the capsule. A closed tube provides an environment free from the typical FOD that autos, trains or aircraft are exposed to. Another possibility is that some part of the communications, control or instrumentation gets dislodged and protrudes into the capsule path. The first and best hazard mitigation is always removing the hazard if possible to do so. Instrumentation and controls infrastructure inside the tube must be secured, wire tied or lock nut fastened whenever possible, to insure they cannot move from their location. FOD and tube (tunnel) caused hazards are ones that are most identifiable and preventable with a Hyperloop totally contained travel envelope. There is a high probability that monitoring of the guideway path via video may be required for certification. This two level approach, reducing the likelihood of debris on the track, combined with monitoring the track condition, is the safest way to protect the capsule from debris collisions.

The nose of the capsule, most vulnerable to forward collisions, is reinforced to resist puncture by debris. (Figure 5) The sloping front geometry will aid in deflecting any object and reduce chances of penetration. Additionally, the entire capsule is constructed as a dual wall containment vessel with nearly 80mm (3.15 in) of separation between walls. An object impacting the outer wall will be slowed, perhaps deflected entirely, and would need to have enough remaining kinetic energy to puncture the second containment wall before entering the inside of the capsule. Small penetrations from FOD and their associated air leaks will be compensated by releasing more air from the onboard pressurized air bottles. The decision to continue to the destination or make an emergency stop will be made by noting the rate of pressure drop as compared to the reserve air supply. Continuing to the destination is in most cases preferred. For events that are more extreme we need to look at the possibility of an evacuation. In the event of a moderate breach requiring evacuation the emergency stopping times, (Figure 3), position/speed of the capsule and location of the next primary exit are used to arrive at optimal evacuation strategy.

The emergency air supply is designed to maintain life support in the capsule in the event of a moderate breach, 51.6 cm² (3.14 in²), through both hulls. In the event that the air tank cannot maintain a safe capsule pressure, the main tube is also fitted with a repressurization system. This system can bring the tube back to atmosphere in minimal time so that the leak rate is diminished and allows air to flow back into the capsule through the breach. Our current design includes 12 repressurization valves per km. A complex interaction between capsule speed/position, next emergency exit in the tube, and location of isolation valves needs to be analyzed before safe repressurization is begun. Once started, full atmospheric repressurization can be achieved in about two minutes. Below is shown Figure 6 depicting the tube pressure rise and times. Note that pressures of 0.5 bar (1/2 atmosphere) can be reached in less than one minute.
Figure 6: Tube Repressurization Graphs – 12 Valves/km

Stranded Capsules and Secondary Evacuations

In the event that a capsule is stranded and cannot move to the primary exit point it can stop at any point in the tube. Every 10km section is referred to as an Isolation Zone. On each side of the zone is located a shutoff valve large enough to seal the entire 10km section. Once a capsule is safely within the isolation zone then the isolation valves are closed and tube repressurization can begin. When the tube reaches atmospheric pressure, about two minutes from the simulations seen above, the capsule emergency doors can be opened (similar to aircraft evacuation doors) and passengers exit the capsule into the tube. The standard requirements for identification of exits and paths in commercial aviation are used to guide passengers to frequent situated tube exit ports. Passengers use the tube exit ports, again similar to aviation escape doors, and exit onto platforms located at pylons. The spacing of the tube exit ports will follow regulations currently used in train travel inside of tunnels and allows all passengers to safely leave the stranded capsule.

A stranded capsule presents the added hazard of not allowing capsules behind it to complete their journey. The preferred option is for rearward capsules to reverse direction and move back toward the origination station or any intermediate station on that route. The origination station is provided with a maintenance area suitable to hold the
incoming capsules and allow passenger debarking. Less preferred options are for the rearward capsules to move to primary exit points and use emergency Docklocks to exit the system.

Several additional hazards result of passenger evacuations into the tube which must be addressed. First is the difficulty of exiting the capsule which is sitting inside of the tube. Depending on the capsule and tube diameter sizes the room to exit along the capsule will be very limited. The currently geometry for the Hyperloop Transportation Technologies system provides a crescent shaped walkway approximately 24 inches wide (Figure 7) along the capsule. US aviation requirements (CFR 14.1.C.25.D.25-810(b)(1), Type II exits) define a minimum walkway of 24" for emergency exits. Due to the round nature of the tube the exit path around the capsule must be curved. Thus, the Hyperloop capsule walkway does meet the general width requirement as stated in the Federal Regulations, but in this case due to the crescent shape, is perhaps not a direct application. Many such issues will require conversations between Hyperloop and the Authority Having Jurisdiction. In all safety cases, HTT intends to meet or exceed existing codes as may be applied. There are other CFR requirements such as step up and step down limitations, the need to have a clear walkway that can be reached without seeing outside the aircraft, door size and location, etc. Our current capsule is designed to meet or exceed all of these requirements with some adaptations required.

A unique hazard to the Hyperloop is keeping passengers (and emergency personnel) away from the extremely strong Halbach magnet arrays located under the capsule. One benefit is that these magnets are aligned in a special way to focus the vast majority of the magnetic field downward. These magnets are located beneath the capsule and for evacuations will be out of reach of the passengers. High magnetic field hazards exist in existing EMS (Electro-Magnetic System) style maglev trains, and typical restrictions and procedures will be incorporated. A final hazard to passenger evacuations inside the tube is the temperature. Due to the thermodynamic work created by the air filling the tube during a repressurization there will be a spike in the tube air temperatures. These higher tube temperatures will abate as energy is transferred through the tube walls and back into the ambient atmosphere. Many variables impact this heat transfer such as local outside temperature, humidity, wind, solar irradiance and shading among those having the strongest effects. Mitigation methods range from localized tube cooling to passenger cooling vests and safety environments. The combination of aviation exit requirements for size and lighting, along with special precautions for high magnetic fields and mitigations for high tube temperatures will all need to be implemented for safe tube style (secondary) evacuations. It is important to remember that tube evacuations are the fourth choice in case of an emergency. The primary choice is to continue to the destination, the second choice is to shelter in the capsule, followed by evacuation through the Docklock, and as a final option we refill the tube with air and move passengers inside of the tube to an evacuation point.

**Braking – Normal and Emergency Situations**

Normal braking forces for the Hyperloop capsule are similar to those of other conventional transportation methods and fall within the range of -0.05-0.3 G. The normal braking methods are of two types that are similar to those in use on Maglev trains. Primary braking is accomplished by reversing the linear induction propulsion system and directing the energy back into battery arrays. The concept of regenerative braking has been used successfully in Maglev systems (Stephan, Ferreira, Mattos, & Oliveira, 2013). This regenerative style of braking directs the energy back into
to the electrical supply system which may be a utility grid or local energy storage method. Multiple phases on the track stator can be used to provide redundancy. Secondary braking is accomplished through using the magnetic fields of the levitation system (Halbach array magnets) above a non-ferrous track material. The movement of the powerful permanent magnets induces an eddy current in the track which induces an opposing magnetic field. This method is quite strong, especially at lower speeds, and can be controlled by adjusting the distance between the magnets and the reaction plates in the track. The multiple magnetic arrays also provide braking system redundancy. The ability to conserve braking energy, combined with using electrical energy sources such as photovoltaic arrays, gives the Hyperloop braking and operational system a lower net energy footprint than current modes of transportation.

There are additional braking methods available to the Hyperloop system. Just as an airplane experiences parasitic fuselage drag plus an induced aerodynamic drag from its wings, the Hyperloop experiences a parasitic drag from its fuselage and an “induced” drag caused by restricted air flow past the capsule. In most cases the aerodynamic forces on the capsule are much less than with aircraft due to the low density of the air inside of the evacuated tube. But the operation of the capsule within a tube provides new options to increase drag (braking) forces. Aerodynamic drag in normal conditions is a function of the square of velocity. In an enclosed tube there are additional factors due to the restricted flow in the limited bypass area (Kantrowitz limit) so at high Hyperloop speeds it is possible to significantly increase drag even at low pressure. Thus, the Hyperloop style parasitic and “induced” drags, referred to as passive aerodynamic braking, are used to effectively slow the capsule. This combination of multiple aerodynamic drags also provides options to increase the braking levels above the normal operation envelope (Figure 8).

Emergency braking G force requirements are higher so that braking distances can be reduced as necessary for optimum headways. As seen previously in Figure 3, capsule separation can be minimized with higher G force braking, thus allowing more frequent departures. Emergency braking uses a combination of normal and expanded braking systems to achieve that higher level G force. Thus, the normal capsule braking system described above is augmented by additional system(s) to create the stronger emergency forces. One considered option is an eddy current system. Eddy currents, as discussed above, induce separate counter-magnetic fields in non-magnetic materials such as aluminum. There are also several active aerodynamic methods which can be utilized in emergency operations. This combined brake system, depicted in Figure 8, can easily attain emergency stop forces of up to -0.6 G as a result of the integration of normal and expanded braking system described above.

Passenger Safety and Comfort during Braking

The deceleration braking profiles expected for a typical Hyperloop journey are planned to be less than -0.30 G (-2.94 m/s²). To put that in perspective, a modest car with 0-100 k/hr (0-60mph) times of 9 seconds has the same acceleration of 0.3 G (2.94 m²). Auto braking forces are usually higher than acceleration forces as all four tires are used to apply brake force equally to the maximum point of slippage. A recent study compared braking G forces for cars equipment with ABS vs non-ABS and found “general” braking forces of ~7.7 m/s² (~.78G). (Kudarauskas, 2007)

From the graph of automobile braking, used as a comparison to Hyperloop braking (Figure 9), normal braking G forces (green line with circles) of 7.5 to 7.7 m/s² (~0.76 to -0.78 G) which are 27-30% higher than a Hyperloop at emergency braking peak. The “emergency” braking forces for typical ABS equipped cars (red line with diamonds)
are 8 to 8.7 m/s² which are 36-48% higher than a Hyperloop emergency stop. One difference should be noted and that is the status of restraints. As opposed to automobile travel which mandates fastened seat belts in the United States, the current plan as proposed by outside safety consultants, recommends passenger restraints while seated during a Hyperloop trip. Seat belts will be available, and recommended for safety while seated, but the freedom to socialize and move during the short trips is deemed to be reasonably safe.

![Figure 9 - Sample Automobile Braking G Forces](Kudarauskas, 2007)

Recent passenger testing with respect to unusual environments and forces has been done for certification purposes of consumer space travel vehicles. Companies such as Blue Origin, Virgin Galactic, Space-X, Bigelow and others have plans to launch vehicles into suborbital space with commercial passengers. One published report for Virgin Galactic (Blue, Riccitello, Tizard, Hamilton, & Vanderploeg, 2012) subjected 77 passengers of various ages (22-88 years) and health to simulated flights using the National Aerospace Training and Research (NASTAR) Center centrifuge. Different flight profiles were tried with peak forces of 2.3 to 6.0 G. The results of testing showed, “.....that most individuals with well-controlled medical conditions are capable of withstanding the acceleration forces involved in the launch and landing profiles of commercial spaceflight vehicles...”. Note: these tests were performed on a wide range of passengers at levels 5 to 12 times greater than a Hyperloop trip. Thus, with comparisons from auto to space travel the range of passenger decelerations in a Hyperloop journey are all much lower and much more comfortable.

**Fire Hazards: Capsule, Li-ion batteries, and Tubes**

The level of fire hazard can be measured by identifying the possible sources of combustible material, presence of oxygen and heat source. The capsule fuselage, stiffeners and skin are a fiber reinforced resin that has flame retardant additives which are rated <25 on the ASTM E-84 standard. This level is in the A group of least flammable materials, similar to that currently used in the latest composite aircraft manufacturing. A key advantage to the Hyperloop is that because the propulsion is 100% electric there is no flammable fuel carried. The certification of cabin material will require following CFR limitations on flammability for seats, walls, carpeting and flooring.

The presence of over 500 kg of lithium-ion batteries to power life support, communication, controls, and low speed propulsion is the largest fire source within the entire Hyperloop infrastructure (excluding stations which are not covered herein). For redundancy, there are two of these power systems, one fore and one aft of the passenger cabin. Either system can operate the capsule systems individually for the duration of the trip with reserves—although at reduced speeds. There have been many incidents with lithium batteries, especially aboard aircraft, which have caused crashes. The fires tend to start quickly and burn very hot as the battery heat reaches a stage of thermal runaway. The Hyperloop battery areas will be isolated from the cabin and well monitored. Due to lengthy commercial
experience with these batteries, even as late as the Boeing 787 fires and grounding (Wikipedia, 2018), and over a million automobiles using hybrid technology, much is known about how to reduce these risks. A significant safety advantage to Hyperloop travel is that ground level is always nearby and thus for certain hazards, such as cabin fire or smoke, cabin depressurization or passenger danger, the capsule can more quickly stop and evacuate (<3 minutes) than it takes an aircraft to descend, change course to the nearest airport, land, stop and begin evacuation.

The tubes within which the Hyperloop travels provide an envelope of safety which must be protected from fire and smoke. The most likely tube materials are steel, fiber reinforced resins or concrete. Although steel is being currently tested as the primary material it is important to cover possible future materials for comparison. Within the tube is fitted the propulsion and levitation guideway, an analog to the tracks for a railroad system. The guideway will be constructed of non-flammable metallic materials, including induction motor coils which require wire insulation at the stator windings. Flammability requirements for wire insulation are taken from the aircraft industry (CFR 25.851-25.869 including Appendix F) Heat from the propulsion and braking systems must be transferred through the guideway and then dissipated through various temperature sinks into the tube shell. The heat buildup due to emergency braking is included in the thermal calculations to reduce temperatures at the propulsion coils and stay well within the thermal rating of the wire insulation.

**Pachen Effect – Arcing in Low Pressure Environments**

Among the unique challenges to building a safe Hyperloop system is that the large voltages within the guideway, and to a lesser extent in capsule bogies, coupled with a low pressure environment creates a high arcing potential. This potential is not only a factor of conductor separation, but in the case of operation within a vacuum environment, includes the ambient pressure conditions surrounding the conductors. This hazard has been known since Friedrich Paschen ran voltage tests in the late 1880s comparing arc distances to ambient pressure in the presence of different gases. Space flights have dealt successfully with this hazard to prevent shorting of circuits by using these well-known relationships. The graph below (Figure 10) shows that at typical operating conditions of 100Pa (0.75 mm Hg) and 1000V that a conductor spacing of 9.33 mm is required in air (0.75 mm Hg x 9.33 cm = 7). The relationship between voltage and pressure-distance is not linear and varies significantly by gas type. Luckily, air outperforms most gases as an insulator in typical tube conditions. The science, and prevention, of low pressure arcing is well known and it can be applied to the Hyperloop system.

![Figure 10 – Pressure-Electrode Spacing Required at 100 Pa (0.75mm Hg) and 1000V in Air](image-url)
Conclusion

The development of Hyperloop as the 5th mode of travel has the potential to provide a revolutionary transportation alternative in the rapidly evolving modern world. Hyperloop has many inherent safety and performance advantages over existing transportation methods, however like all modes of transportation it has associated risks and hazards. This paper has discussed some of the development efforts at HTT to identify those risks and hazards and mitigate them through careful capsule design and operational procedures. These and other efforts will continue through the design, verification and certification stages of this new transportation technology. This process along with on-going development of new standards and regulatory activities will result in Hyperloop installations that exceed the expectations for modern transportation systems.

References:


