Analysis of Fire Hazards Associated with the VacTrain Design

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Abstract

A vacuum train (VacTrain) refers to the concept of a high speed transportation system which consists of a magnetically levitated train (Maglev) that travels in an evacuated tunnel. Several studies have been conducted on the existent magnetic levitation train and its fire safety aspects. However, no research exists for the fire hazards in the vacuum train itself. This project analyzes the fire safety characteristics of systems closely related to the VacTrain and its environment in order to predict its fire hazards. Based on these findings, the most efficient suppression systems and evacuation techniques were proposed.

Acknowledgements

This dissertation could not have been possible without the guidance and support of Professor Rangwala, Professor Meacham and Professor Pavlov. Not only did they serve as our IQP advisors but they also challenged and encouraged us through this entire project. We would like to sincerely thank you for your insightful critiques and patience during the whole process. We would also like to thank everyone who helped us with the finalization of this project by providing us with timely feedback.

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1 Introduction

Rail transportation systems are a common means of public transportation used around the world. To date, the fastest is the magnetically levitated train (Maglev) which is located in countries such as United Kingdom, China, Japan, and Germany. Following the development of the Maglev train, further research has been conducted to see if this system can be made more efficient, faster and to enable travel between outstandingly long distances. This research led to the development of the theory of the "Vacuum train (VacTrain)". The VacTrain is presumed to be an efficient transportation vehicle which will be able to reach high velocities travelling through a vacuum tunnel. This idea was first envisioned by Frank Davidson, a former MIT researchers and Yoshihiro Kyonati, a Japanese engineer.

Despite all of its advantages the VacTrain will most inevitably have its share of weaknesses. Fire related aspects have a high priority in any new technological development, hence this report will be an evaluation of fire hazards, the proposed VacTrain could contain. Since the VacTrain is purely a theory, the fire hazard assessment will be done separately on passenger trains, tunnels and Industries that use vacuum environments. Once these three existing systems have been assessed under a fire hazard analysis perspective, the data obtained will be combined to create a fire hazard assessment for the VacTrain.

A simple overview of this evaluation can be laid out as follows;

- Analysis of existing train designs – compiling data of Amtrak, Maglev, and bullet trains.
- Analysis of existing train tunnel designs.
- Analysis of fire hazards in existing train and tunnel systems.

- ❑ Analysis of industries which use vacuum and underwater fire safety systems – Extraterrestrial microgravity conditions used at NASA, submarines and other extreme settings related to the VacTrain.

- ❑ Compile all the above to Recommend Mitigation and suppression techniques for the fire hazards established above.

As a result this report will assess recommended materials, effective suppression technique(s) and feasible evacuation technique(s) needed for a VacTrain in a hazardous situation. Collectively all this information will help create a fire hazard assessment and finally detail the possibility of a fire safe "VacTrain".

2 Background information – VacTrain & Vacuum tunnel

The VacTrain is a conceptual transportation technology that combines the Maglev train with an evacuated tunnel spanning across a country or even across continents. It is an efficient transportation system void of friction and air drag. It is a faster and more environmentally friendly alternative compared to other available means of transportation and presumably the next step in transportation technology after the Concords.

The concept of the modern VacTrain was pioneered around 1910 by the WPI alumnus, Robert Goddard. The designs of the VacTrain were produced during his time as a university student; the train was to travel from Boston to New York at an average time of 12 minutes. The original designs were only found in 1945 after Goddard's death. During the 1970s, the VacTrain made headlines when various engineering articles were published by a leading advocate of RAND, Robert F. Salter. Since the Maglev technology was still poorly established during the time, Salter proposed steel wheels instead. In his design, the train was to accelerate into the tube by opening the chamber's door to the tube to intake enough air behind the train. Then the train is to further accelerate by relying on gravity until it reaches cruise level. To decelerate upon arrival, the air ahead of it was to be compressed and vented. To make up for the loss due to friction of air leaking from the edges of the train, pumps are set up at stations. Thus the train was to run without a motor. Instead it was based on gravity and atmospheric railway propulsion. Although this system conserves energy it also limits the speed of the train from reaching sonic speed; hence the proposal was not for a transcontinental means of travelling but distances within hundreds of miles.

A route for the train to travel was also set up, "…with nine stations, one each in DC, Maryland, Delaware, Pennsylvania, New York, Rhode Island, Massachusetts and two in Connecticut."[1] A commuter version of the train was also designed for San Francisco and New York; this version was longer and heavier, it would require less air and more gravity to propel itself compared to the design planned for intercity travel. Salter believed that this means of transportation would be more environmentally friendly compared to surface and air travel. However the plans never made it to the next stage.

During the time these reports were being published, national prestige was of consideration as Japan's bullet train was in operation and research was being conducted on the Maglev train. The Maglev train is a transportation system that suspends, guides, and propels the train utilizing electromagnetic forces. Using this technology the trans-planetary subway service was to be established by the American Planetran in the United States which reduces the travel time from New York to Los Angeles into a mere hour. This tunnel was to be built several hundred feet deep in solid rock formations. The alignment was to be taken care of, by using high precision tools that entail lasers and tungsten probes to melt through igneous rock formations. Maintaining partial vacuum is pertinent to reduce drag. "A trip would average and subject passengers to forces up to 1.4 times that of gravity, requiring the use of *gimballed*[2] compartments." Enormous construction costs (estimated as high as US $ 1 trillion) was the primary reason why Salter's proposal was never built,"[3] which remains to be the primary reason for the unfulfilled proposal.

The most recent proposal for the VacTrain is by a channel tunnel project founding member, Frank Davidson, and a Japanese Engineer, Yoshihiro Kyonati. This design consists of the underwater vacuum tunnel running from North America to Europe and aiding the Maglev to travel the distance within a short period of time.

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[1] Absoluteastronomy.com – Vactrain, Background
[2] A gimbal is a pivoted support that allows the rotation of an object about a single axis
[3] Absoluteastronomy.com – Vactrain, Background

2.1 The design

The latest proposed Tran-Atlantic VacTrain Design taken from pop-science is shown below. The vacuum tunnel consists of three different sections: The Main vacuum compartment, the service tunnel and an evacuation tunnel.

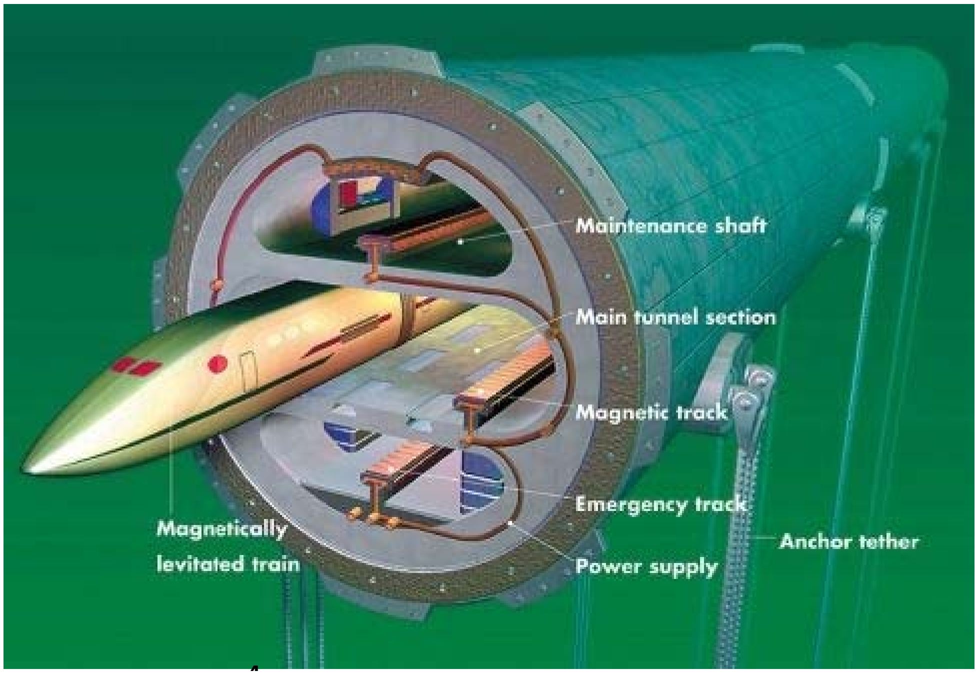


Figure 1 - Trans-Atlantic VacTrain Design – "vacuum Tube Train" by Mika Grondahl[5]

[4] Popsci.com - Trans-Atlantic MagLev, Posted 11.12.04

3 Fire hazards in the VacTrain

A helpful way to start off this fire hazard assessment is by outlining the possible sources of fire in the VacTrain design. This aids to focus on the parts of the VacTrain system which is more prone to fire; detection and suppression techniques with reference to these sources will follow further on in the report.

3.1 Probable hazards in the VacTrain:

- ❑ Electrical components that run along the service tunnel –

  This includes all the wiring which will provide power to the train, vacuum pumps and all three tunnels within the vacuum tunnel. The risk factors of the electrical components are;

  - ✓ Overheating – If there is a power surge, the wires will heat up more than its heat capacity and cause a fire within the tunnel.
  - ✓ Short circuiting – There can be damages in the wire shells which might expose the wires, resulting in sparks which will lead to a fire hazard.
  - ✓ Water leaks in the tunnel – Since the tunnel runs mainly under water, there can be leaks in the tunnels surface which will act as a conducting material for the electric wires.

- ❑ The service tunnel and the evacuation tunnel –

  Both these tunnels will have regular atmospheric conditions. A fire will spread faster under these conditions. However, the evacuation tunnel will be constructed according to regulations with materials that are least prone to ignition.

- ❑ The cabin of the VacTrain –

  The cabin of the VacTrain will have equipment and components which are most likely to ignite. Materials such as cushions, curtains have a high probability of spreading the fire within the compartments. The oxygen supply for the passengers will also help the fire to spread faster. The fire load for the cabin is quantitatively compared to that of an air plane cabin.

- The vacuum pumps –

  In addition, the operating temperature for most vacuum pump fluids is in the range of 195°C to 220°C. Overheating in the fluids will occur if the vacuum pumps are operated near or at atmospheric pressure, and thus the temperature will reach auto ignition stage. Also, if the power supply cord for the vacuum pump is undersized, a drop in line voltage might occur and the power loss will cause the vacuum pumps to overheat and become a potential fire hazard. Furthermore, wirings should not be placed at close range from the exhaust since the air from the exhaust can become extremely hot and incur damages to surrounding areas.

- The high speed of the VacTrain –

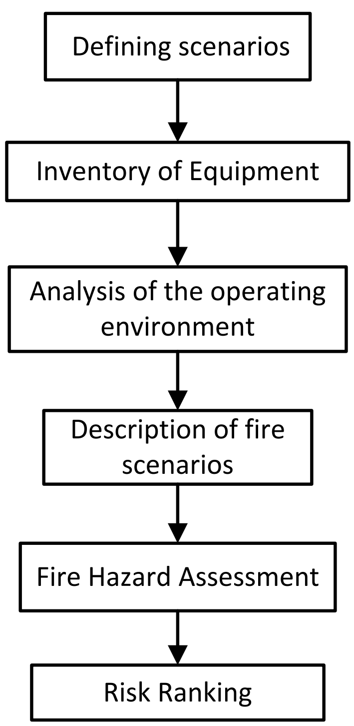
  The VacTrain has an estimated top speed of 8000 km/h. In case of a fire incident, bringing the train to a complete stop would be the first priority. If the train were to have a crash landing it would damage the tunnel and cause the entire system to collapse.

4 Fire hazard analysis

4.1 Fire hazard analysis techniques

After establishing the probable fire hazards in the system an analysis can be made on the materials to be used and the fire load[5] in the VacTrain. The technique used to make this analysis is entailed in this section. Hazard analysis can be used for determining hazards that might be possible in an existing environment or for planning and design of new environments. Fire risk analysis test and performance criteria focuses on providing high levels of fire performance for combustible materials found in rail transportation systems and the "VacTrain".

4.1.1 Steps to perform fire hazard assessment:



Account for fire scenarios that might occur in the future.

A detailed account of the equipment and materials that make up the system.

Operating speeds, tunnel length and the exterior terrain.

Use the inventory and the combination of ignition sources that can result in a fire.

Each of the described scenarios must be assessed as to how much damage it may cause.

Prioritizing the scenarios according to the level of damage it may cause.

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[5] Fire load - The total fuel contributed to a fire by systems contents, combustible materials used in its construction, and/or its finishes.

4.2 Material analysis / Material flammability

The first step in making the fire hazard analysis of any system is the evaluation of the materials with which the system is made. The VacTrain is predicted to be made of state of the art composites, but in a straightforward hazard analysis perspective these materials can be categorized into solids, liquids and gases. To explain the concept of combustion the next step is to analyze the flammability of these materials. These materials have been evaluated according to the rate of burning, how it can be ignited and how it can be controlled.

Note: - Liquids have not been subjected to this analysis because the VacTrain is a not a fuel based concept. Also the tunnel will be a complete vacuum; hence there will be no use of fluids except in the vacuum pumps.

[6]	Solids			Gases	
	Flexible Materials	Structural Materials	Dust	Gases in Pressurized Containers	Cabin Air
Rate of burning	High rate of burning. High Effluence	Moderately High (Lower than Flexible Materials) High in Molten forms	Dependent on particle size and concentration of dust cloud	Very High (Since Pressure makes the gas more flammable)	High (since Cabin Air will consist of 73% Oxygen)
Ignition Control	Flame resistive materials, treatments and protective Materials	Flame resistive materials, treatments and protective Materials	Static floor panels for dust collection	Storage and handling safeguards	Inerting of atmospheres
Examples	Textile and cushioning	Steel and composites	Dirt and Metallic particles	Oxygen and Nitrogen	Atmospheric gasses

Table 1 - Material analysis / Material flammability

To determine flammability hazards a large number of parameters come into the scenario. The different aspects of flammability of materials include chemical composition, physical properties and geometric configuration. It is very important to use a variety of flammability test methods and models in order to

[6] Section 6 - Chapter 17, NFPA FPE Handbook

assess realistic fire scenarios more accurately.[7] One such model of flammability of the materials within the train system is that of fire load.

4.2.1 Fire load

As mentioned earlier the VacTrain is expected to be made from revolutionary composites. In order to assess the fire hazard involved in these materials the fire load must be calculated. This is the load of combustible materials per square foot of floor space. Since the VacTrain is a conceptual idea, any direct estimation of fire load will be unrealistic, therefore a comparison is made. The environment that relates closest to the VacTrain is that of an airplane cabin. As illustrated below this will help determine the amount of time that is available for detection, evacuation and suppression. The main difference between the aircraft and the VacTrain would be the outside environment. Evacuation and detection techniques would change because of the tunnel walls around the train.

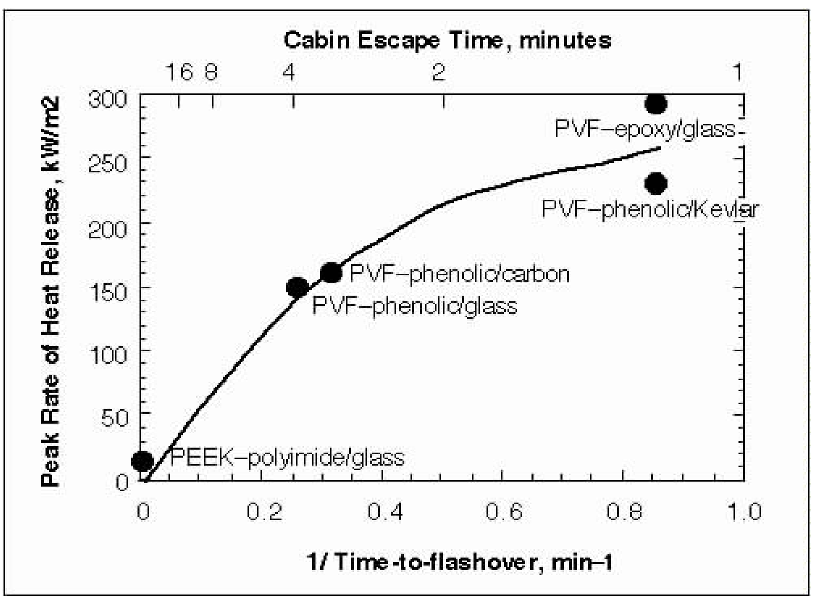

Figure 2 – Heat Release Rate vs. Time in Air Plane Cabin
(Federal Aviation Administration of fire Safety)

[7] Section 2.3 – Flammability of Materials, NFPA FPE Handbook

4.2.1.1 Predicted fire load in VacTrain Cabin:

This graph represents the rate of heat release in kW/m^2 of materials in a cabin against the inverse of the time-to-flashover. Flashover[8] is when the compartment will burst into flames. In scientific terms flashover is caused by the radiation feedback of heat, meaning the energy absorbed by the contents of the cabin helping heat up the combustible gases and furnishings to reach their auto ignition temperature. The buildup of heat in the room triggers flashover.

Airplanes in general use PEEK – Polyimide/glass[9] foams because of the lightweight and fire resistant properties. This composite is used to make aircraft tray tables, aircraft windows and canopies, air-return grills, arm rests, avionics instrument panels, bearings, bushings, interior components, seals and wire wrap insulations. Composites like PVF – phenolic/glass or carbon[10] has good resistance against fatigue, weathering, fungi, salt, Humidity, water and oil. The galley, lavatory surfaces that face the aisle, ceilings, baggage racks, lavatory interiors and door liners are typical applications for decorative plastic laminates like PVF – phenolic/glass or carbon[11]. PVF - Epoxy/Glass, PVF – Phenolic/Kevlar are used in the encapsulation or casting of various electrical components and powder coating of metal substrates.

These three types of composites are generally used in aircraft cabins and can be considered to be used in the VacTrain cabin as well. This comparison is done based on the similar environments of the VacTrain and airplane cabins. Assuming that the VacTrain cabin will use similar composites, it can be seen from Figure 2 that materials such as PEEK-polyimide/glass has a very low rate of heat release so the time-to flashover is almost infinite. However, the time to flashover for PVF-phenolic/glass or carbon is lower. Also for materials like PVF-epoxy/glass the time to flashover is the least, thus allowing the least amount of time for suppression and evacuation.

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[8] Workingfire.net - Flashover By Ret. Chief Vincent Dunn
[9] Curbellplastics.com - Aerospace and Defense Applications - *Curbell Plastics*

[10] Federal aviation administration fire safety - Appendix C:Materials Used in Aircraft
[11] alican.com - DIFFERENT TYPES OF PLASTICS, The Society of the Plastics Industry (SPI)

4.2.1.2 Changes in fire load graph with relation to the VacTrain:

From the data represented in the reference below[12], an average of 15400 lbs of combustible materials exist in aircraft cabins. Polymeric cabin materials have an effective heat of combustion of about 35 MJ/kg in a fire. Therefore the fire load in the average cabin would be 7000kg*35 MJ/kg (i.e around 245000 MJ). The plane used in this approximation a Boeing 747-400[13] which weighs approximately from 390,000 lbs to 410,000 lbs. Comparatively the weight of a three car Maglev train weighs about 270,000 lbs. Taking into account, the ratio of the amount of combustible materials to the weight of the plane we can estimate the VacTrain to consist of approximately 10,000 lbs of combustible materials. Considering all these values we can say that the average fire load in a three car Maglev to be 4725*35 MJ (i.e around 165375 MJ). The VacTrain cabin is predicted to be made of similar materials so we can say the fire load estimation is approximately the same. Although the fuel factor can be completely ignored in a VacTrain cabin, oxygen canisters would give a much higher rate of heat release. This would bring about slight changes to the curve and the estimation to the total fire load in the system. The time to flashover would change according to the fire load of extra materials needed for the VacTrain.

"……Carryon luggage represents an additional fire load, neglected in the calculation, which would be minimized by containment in fireproof stowage bins."[14] Another aspect to contemplate while calculating fire load is the luggage. The change in value that it would bring to the total fire load value would differ with a couple of parameters. At different travel times, there would be different amounts of luggage on the train. Also the type of materials carried in the luggage will be different and the flammability of these materials is one of the most important factors. Any of these materials could be the reason for heat buildup within the train and might cause severe damage to the system. But as mentioned in the reference, using fire proof materials to make storage cabinets would help isolate the flammable materials in the luggage from the fire itself and provide extra time to flashover.

[12] Federal aviation administration fire safety – Fire Research, Aircraft cabin Material
[13] wikipedia.org - Boeing 747-400
[14] Federal aviation administration fire safety – Fire Research, Fire Hazards of Aircraft Cabin Materials

5 Rail transportation systems

Now that flammability of the different materials predicted to make up the VacTrain has been evaluated. The attention should be on making this VacTrain completely fire safe by decreasing the probability of any kind of fire.

Despite the Vactrain being a highly modern technology, it is still applicable to compare and evaluate the detection and mitigation techniques of existing train systems given the resemblance in the basic concept of operation of all trains. Looking into existing rail transportation systems will help predict the detection, suppression and evacuation techniques required for the VacTrain. The most relevant rail transportation systems were found to be Amtrak, diesel electric locomotives, electric locomotives and Maglev trains.

Types of Train Systems	Possible sources of fire	Detection	Mitigation and Evacuation Techniques
Amtrak Amtrak passenger trains are electric powered trains with fixed train sets	• Over-Heated Engine • Electric sparks in the Engine • Wires in Electric cabinets	• Temperature Sensors • Commercial Gas Detection System • fire Gas Detection System	• Deluge sprinkler • Gaseous fire suppression systems • Engineer escape hatch on the roof of the train. • Folding ladders • Evacuation ramp at the bottom of the train. • Evacuation windows
Diesel Electric Locomotives A Diesel electric locomotive uses a diesel engine that drives a main traction generator	• Over-Heated Engine • Fuel Leak • High voltage faults in electric compartments • Over-Heating in the Generator	• Combustible gas detector • Flue Gas Monitors • Gas Leak Detection • Temperature Sensors	• Hot Engine Protection: devices • Engine Crankcase Protection • High-Voltage Detecting Ground relay • Emergency fuel cutoff Switches • Main Battery Knife Switch • Portable fire Protection Equipment
Electric Locomotives Electric Locomotives are specifically designed for passenger transportation in major metropolitan areas	• Electric sparks between overhead wire contact • High voltage faults in electric compartments	• Power surge meters • Digital Temperature Sensors	• Emergency Stop Buttons • Manual Pantograph Ground Switch • Portable fire Protection Equipment

	• Over-Heating of wires inside the train • Ignition of air compressors		

Table 2 – Rail transportation systems

5.1 Maglev trains

The other most important rail transportation system to assess is the Maglev train, because it is the main component in the VacTrain system. For reference to the technology it uses and its relation to probable fire hazards, evaluating it is necessary.

This Maglev train uses strong electromagnets for high speed travel. As the name states, this train employs basic magnetic principles, where opposite poles attract and like poles repel. Strong electromagnets are used to create extremely strong magnetic fields which allow the Maglev train to run over a guide way in exchange of the old steel wheels and tracks.

Maglev train specifics;

- Power for Maglev trains is used to accelerate the train, and may be produced when the train slows down. The amount of power used can vary depending on the region the Maglev is operating in.
- Maglev train tracks are built based on EMS (Electromagnetic suspension), EDS (Electrodynamics suspension) or Induc-track system(electromagnetically induced track). The Maglev train tracks has a magnetized coil running along the track, called the guide way, which repels large magnets located on the train undercarriage. The guide way enables the train to levitate between 0.39 to 3.93 inches above the track[15].
- As a result the Maglev train has the capability to reach speeds of around 310 mph. The fastest Maglev Train, the ML X01 has a recorded top speed of 550km/h or 344mph.[16]

The Maglev is the most efficient train transportation system to date. However the air drag on the train increases the amount of energy used, as a square law on speed. The vacuum tunnel idea was thus introduced to decrease the amount of air drag due to which the velocity increases. The power

[15] Wikipedia.org - Maglev (transport)
[16] High Speed Rail (HSR), The MLX01 By Oliver Keating

consumption is fairly lowered but still an ample amount of electricity is required to accelerate the train and keep it running at a certain speed.

So, basically the idea of the VacTrain as mentioned several times previously is to decrease the amount of air drag and power consumption that the current Maglev is subject to. In economic terms power consumption is a very important factor but in a fire hazard analysis the amount of power consumed might prove to be a major fire risk, in terms of the electrical equipments being used. Hence, the next section explains the relation of power consumption to the fire hazards it may cause for the VacTrain.

5.2 Power consumption and its relation to fire hazards

The different voltage ratings[17] and the approximate amount of power consumptions of different types of trains are listed in table 3[18]. According to the table the vacuum train requires a large amount of electrical energy to help it reach its operational velocity for which there will be large amounts of wiring running through the tunnel. The main power requirement for the vacuum tunnel will be to induce the electromagnet that helps accelerate the train and to run the vaccum pumps which will help maintain the vacuum inside the tunnel. Several high voltage supplies are needed to provide a large enough power supply running contionuosuly thoughout the tunnel since the electromagnet needs a constant outsized electric supply to keep it running. Hence, the wiring is prone to overheating and is a potential fire hazard.

Types of Train Systems	Voltage Rating	Power Consumption	Maximum Velocity, Km/hr
Traditional Trains	1000 V DC	8 X 150 KW	70
High Speed Trains	25 kV AC,60HZ	24 X 275 kW	285
Maglev Trains	12 kV DC	4.2 MW	550
VacTrain	Predicted : 6 kV DC	N/A	8000

Table 3 – Voltage, Power Rating of Train systems

[17] Hitachi-rail.com - High Speed Trains Delivery Records
[18] Hitachi-rail.com - Commuter Service Trains Delivery Records

5.2.1 Fire safety measures related to power consumption

The wiring through out the tunnel will be so extensive that at every interval there should be optical smoke and heat detectors present. These will help detect even minimal amounts of smoke and heat from electrical short circuits;providing even more time for suppression and evacuation.

5.2.2 Back up generators:

In the case of power failures standby generators can supply enough electricity to keep the Maglev running. These generators[19] will start automatically upon power failure to avoid the train from skiding on the track and creating more sparks, acting as a potential ignition source. The solution could be aircraft style batteries onboard the Maglev train which is charged by the linear generators, at the station stops. The batteries would provide backup power for the Maglev during either a propulsion system failure or a power failure to ensure that the train always stops itself to safety.

[19] Windana Research (Ptv) Ltd - Guided Transport, Maglev

6 Transportation tunnels

With regards to several other topics, the VacTrain is a combination of the Maglev train and a tunnel system. Therefore, an investigation of existing tunnel systems will help create an overview of the vacuum tunnel. All existing types of train tunnels can be categorized into three parts: above ground, underground and underwater. Each categorization was individually analyzed to understand the possible sources of fire and mitigation/evacuation techniques.

Types of tunnels	Possible sources of fire	Detection[20]	Mitigation and Evacuation Techniques
Aboveground	• Electric wires • Sparks from Metal framework • Lights • Concentrated dust particles	• Linear heat detection system • Flame detectors • Smoke detection system	• Passive fire protection - fire protection boards, spray mortar protection, polypropylene fibers, fire safe concrete • Active fire protection – sprinklers, water-mist systems, water curtain, and other means of compartmentation. • Alternative exists alongside the tunnel walls
Underground	• Electric wires • Damp conditions reaching the interior • Lights • Concentrated gases	• CCTV image detectors • Spot detectors • Underground Telemetry Systems • Relative Humidity Sensors	• Passive fire protection - fire protection boards, spray mortar protection, polypropylene fibers, fire safe concrete • Active fire protection – sprinklers, water-mist systems, water curtain, and other means of compartmentation. • Alternative exists alongside the tunnel walls
Underwater	• Electric wires • Water leaks • Lights • Concentrated gases	• Linear heat detection system • Flame detectors • CCTV image detectors • Spot Detectors • Concrete crack/leak detectors	• Pre-cast concrete lining • A separated maintenance/evacuation tunnel • Pre-cast concrete lining[21]

[20] An Overview of the International Road Tunnel Fire Detection Research Project by Z. Liu1, A. Kashef, G. Lougheed, J. Z. Su and N. Benichou
[21] Workshop on safety in tunnels and underground structures - Riyadh, Saudi Arabia - Ministry of Transport, November 2006

		• Wet Differential Pressure Sensors	
	•	•	•

Table 4 – Existing Transportation Tunnels

In this modern world the use of underwater tunnel is no longer a novelty. The concept has been in developmental stages for many years and became a reality for many countries. Although these tunnels were designed for traveling shorter distances and in some instances trains are not even involved, the concept of the risk of being stuck in an underwater tunnel still remains the same. Focusing on underwater tunnel fires will help design a fire safe underwater vacuum tunnel. Hence, the next section focuses on a fire incident that occurred in the Eurotunnel and solutions that might counteract such incidents.

6.1 Eurotunnel fires

The Eurotunnel is a 31.4 miles undersea tunnel that stretches beneath the English Channel, connecting Folkslore Kent in England to Coquelles in Northern France. The tunnel contains three tubes; two of the tubes carrying passenger trains and freight, and a third tube for maintenance and evacuation purposes. Since the tunnel opened in 1994, there had been three fire incidents up to date. The first recorded fire occurred on November 18, 1996, when a fire broke out on a heavy goods vehicle shuttle wagon. The suspected reason behind the 1996 fire was an act of arson. The heat of the fire reached 1800°F, damaging 46 meters of tunnel. All three recorded fires seem to have occurred on truck shuttles that carried flammable materials; the open sides of the shuttle cause the danger as they allow air to come in contact with the blazing materials. The worst recorded fire incident occurred on September 11, 2008 when the brakes of a freight train overheated resulting in the explosion of a tire. The explosion quickly set fire to the entire cab, engulfing other vehicles within minutes. Similar to what happened in 1996, the tunnel acts as an oven, causing the heat from the blazing flames to reach a temperature of 1800°F;

taking 300 firefighters almost the entire night to douse the fire. The damage far outweighs the fire incident in 1996[22].

The vacuum tunnel used for the VacTrain has a similar design to the Eurotunnel. Furthermore the VacTrain will initially be used to carry freight, which could be dangerous if flammable goods are transported. In relation to this fire hazard scenario, the vacuum tunnel could be contaminated with oxygen and hydrogen and the fire might blaze through the entire tunnel. To prevent such a case from occurring, the tunnel walls should be equipped with gaseous extinguishing systems that do not damage electrical parts of the VacTrain. Also all the tunnel sections should be readily equipped with vacuum pumps to avoid smoke from filling up the tunnel.[23]

[22] Guardian.co.uk - Channel tunnel fire worst in service's history, Friday 12 September 2008
[23]Truck Explosion Causes Major Fire in Channel Tunnel by Gordon Rayner, David Millward, and Aislinn Simpson, The Daily Telegraph - September 12, 2008

7 Related environments

7.1 Submarine fire incidents

As pointed out above the proposed VacTrain tunnel design is primarily an underwater schematic, which is supposed to run under the Atlantic Ocean from the Americas to Europe. Research on underwater transportation systems like submarines might help formulate suppression and evacuation techniques for the vacuum train system.

7.1.1 Russian submarine accidents

Fire incidents in Soviet submarines like the K-8, K-219, and K-278 usually started with an explosion in missile tubes or in an overheated diesel generator system. This eventually caused short circuits in the electrical systems which escalated fire growth. Fumes from the fire, spread to the compartments making the environment more toxic for the occupants. Due to the weak suppression and evacuation techniques these submarines ended up being heavily damaged and sunk to the bottom of the ocean. In other incidents like the K-3, K-19, K-47 and K-131 the fires started in the submarines hydraulic system. The fire spread into other compartments which were sealed off and quarantined. An automatic extinguisher which uses CO_2 was used to diminish the fire. The causes of death in these scenarios were mainly the toxic fumes and first degree burning, but many lost consciousness due to the CO_2 in the suppression systems. The main evacuation technique was surfacing the submarines and using rafts to carry occupants to safety.

In all the incidents the source of the fire was quarantined, the submarines surfaced immediately and the usage of CO_2 proved potentially harmful. In a vacuum train fire incident, strategies like the use of automatic suppressant devices following the isolation of the fire source and surfacing of the harmed parts can be used.

7.2 Fire incidents in extraterrestrial vacuum environment

On February 23, 1997, a fire broke out in the kvant-1 module on the Russian space station MIR. The fire burned for about 90 seconds before it was extinguished using three, two liter water-based foaming extinguishers. The fire occurred when an astronaut ignited an oxygen canister, and suddenly the flame blazed out of control. The smoke from the flame was quick-spreading and it filled a multi-module complex including their only “lifeboat”, the Soyuz. Fortunately, the life-support system onboard was able to clear out the smoke eventually. The damages to the hardware were not due to the burn, but from the excessive heat of the fire.

Similar to the situation that the Russian space station MIR faced, the VacTrain will also use oxygen-supplying canisters at any emergency. Therefore it is necessary for the VacTrain to be equipped with extinguishing systems, preferably heat-activated gaseous fire protection systems that will prevent damages to electrical controls and equipments. Installing an air purifier might help to deal with the smoke to avoid its spread in case of fire in the passenger compartments.

Finally, using all these incidents from the related industries, the probable detection, suppression and evacuation techniques for the Vactrain can be detailed.

8 Evacuation techniques

In a system failure in any kind of transportation system, the highest priority is the life of the passengers. Since this project will ultimately provide a feasible fire safe VacTrain design, it is very important to look into evacuation techniques for similar systems. To prepare for a worst case scenario, evacuation techniques must be decided ahead of time to at least save the lives of the passengers. In order to create a sensible evacuation scenario, the passenger evacuation concept used for the Munich Transrapid can be applied.

8.1 Design of the Munich Transrapid

The simulation for the Munich Transrapid was done on an isolated compartment. This compartment has the following dimensions[24].

Section length (avg. per compartment) - 1003.93inches (25500mm)

Outer width - 145.66inches (3700mm)

Distance between exits (doors) - 486.77inches (12364mm)

Also since this simulation is used as a comparison, the following boundary conditions/data must be taken into account.

Triple-section vehicle	Without luggage comp.	With luggage comp.
Seats	156	148
Passenger capacity when all seats are occupied, 1 person/m² standing room (normal capacity)	239 persons	222 persons
Passenger capacity when all seats are occupied, 320 kg/m² standing room, approx. 4 persons/m² standing room (max. capacity)	449 persons	412 persons

Table 5 - Munich Transrapid compartment capacity

[24] Design and Development of the Transrapid TR09 by Dipl.-Ing. Michael Tum, *Kassel, Germany, Deutsche Bahn AG,* Christian Harbeke

8.2 Simulation

The simulations[25] for evacuation inside the vehicles were intended to show that all passengers of a section could rescue themselves into neighboring compartments. To illustrate this, two different Hazard Scenarios were applied. Along with the hazard analysis, both fire scenarios, shown in Figure 3, were assessed as the incidents with the highest endangering potential, i.e worst-case scenarios.

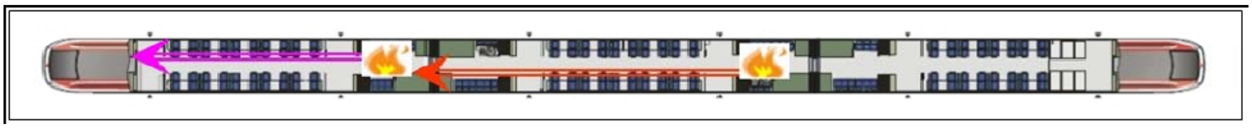


Figure 3 - Evacuation of the middle section and investigation of the tailback situation in the end section
(Passenger evacuation concept as applied for the Munich Transrapid)

A maximum vehicle capacity of 412 passengers was assumed. These passengers were assumed to take a single directional self rescue path (i.e. every passenger will exit in the same direction). The time to completely evacuate passengers from the middle section into an end section, including reaction time of 164 persons, amounts to about 4.2 minutes.

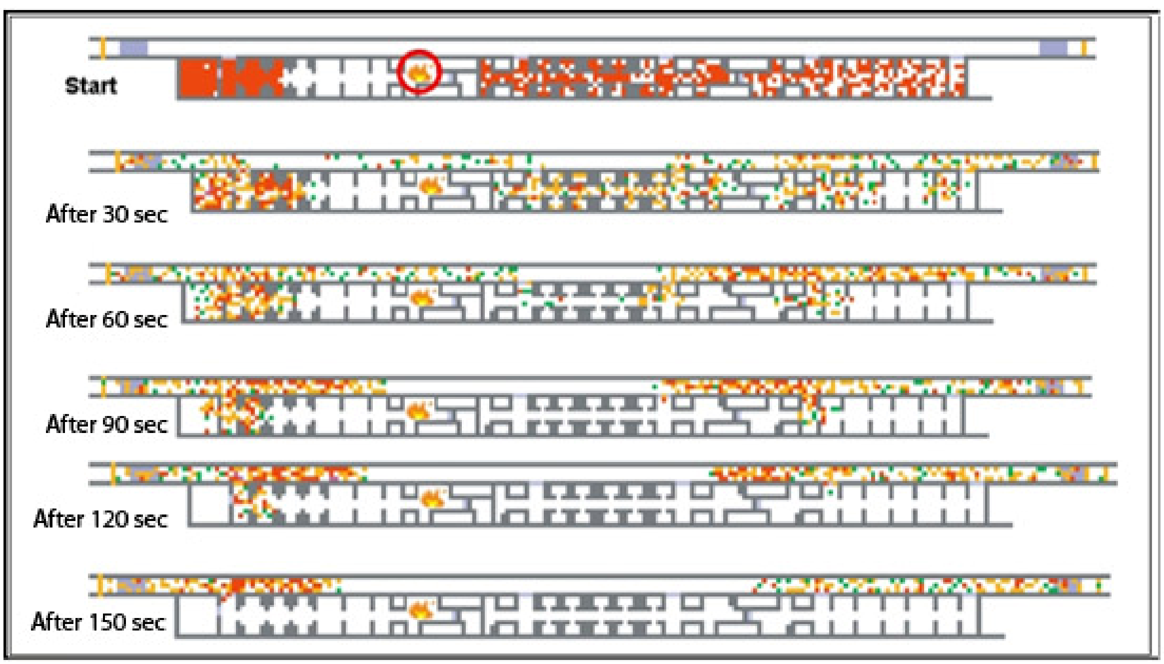


Figure 4 – Evacuation of the Maglev vehicle in a fire located in the bend section of the intersection of two zones
(Passenger evacuation concept as applied for the Munich Transrapid)

[25] Passenger evacuation concept as applied for the Munich Transrapid, taking particular consideration of possible fire incidents by Author: Dr. Jürgen Heyn, Co-author: Thorsten Janssen, Co-author: Thomas Graf

Evacuations tests that can be related to the VacTrain result in an evacuation time period of about 2 to 5 minutes. Simulations of evacuations show that it takes about two minutes for 142 persons to exit the vehicle. However, taking into account the passenger confusion while exiting at the evacuation stopping areas, evacuation time is extended to 2.5 minutes. This scenario has been simulated according to passenger density as shown in figure 4.

This estimation is done taking into account that the VacTrain compartments are about the same dimensions of the Munich Transrapid. By close comparison to the simulation results, the evacuation strategy for the VacTrain would require the vacuum tunnel to have a number of ports. These ports would enable the VacTrain to dock and safely evacuate passengers into the evacuation tunnel.

Also by comparing to the research done on lane cabins, in section 4.2.1 (fire load) the passengers would have approximately 10 to 12 minutes before the Flashover. Values such as these by comparison provide a basic idea of what the evacuation time frame is. The VacTrain has a top speed of 4970mph (8000km/h). This can be used as an advantage when considering the exit strategy. The recommended strategy would be to have evacuation docks built in the vacuum tunnel. These docks will be spaced out equally and the distance between them will be determined by considering all the different time constraints. These evacuation docks will allow the VacTrain to provide quick exists for the passengers. Also these docks will be the connection between the vacuum tunnel and evacuation tunnel. Once in the evacuation tunnel the passengers will be out of the probable risk.

9 Fire suppression techniques

While prevention is the best measure, "…sometimes it's not possible to prevent a fire. In these instances, it's important to mitigate the fire damage after it occurs. This can mean containing a small fire before it becomes a much larger fire. It can also mean mitigating further damage after the fire department has left."[26] The key to mitigating fire is early detection; therefore it is important to have working detection systems that are maintained regularly. The positioning of the detection system is also a pertinent aspect of mitigation; the compartments and the bathroom stalls should be equipped with them, as well as the cargo hold, and the oxygen canister holding area.

The detection system should trigger the automatic fire suppression systems should be equipped in all the enlisted areas. These automated suppression system should trigger upon the initial phase of a fire breakout to ensure passenger safety and minimal hardware damages. The preferred suppression system for the passenger area is the high-pressure water fog system, discharged from nozzles and equipped in the interior ceiling of the cabin. The cargo area should be equipped with hoses that discharge FireIce® solution into the hazard area.

Another factor is the interior material. The compartment interior should be made of materials with fire retardant properties. This is to ensure that the fire does not engulf the interior in the case that it starts or spreads into the passenger compartments. In addition to the interior, each compartment is to be partitioned by fire-proof doors to achieve isolation of fire in the case where the fire has passed the initial phases.

In order to categorize the mitigation techniques used in the VacTrain system, we have listed information from existing train and tunnel systems. Also from the research done on the Maglev train designs these mitigation techniques have been tabulated as seen in table 6.

[26] Firewaterrepair.com - Water & Fire Restoration Information, Articles On Fire & Water Repair, How To Mitigate Fire Damage

	Types of Environment	Possible Sources of fire	Mitigation Techniques
VacTrain	Cabin	Electrical equipment short-circuiting Highly flammable material (Cushions, curtains etc.)	Deluge sprinkler High pressure water fog nozzles fire retardant materials & fire-proof doors
	Cargo hold	Flammable material Luggage	FireIce®
	Lavatory	Passengers Negligence (e.g – smoking)	High pressure water fog nozzles
	Oxygen Supply	Oxygen leak	Isolated supply room Automatic shut-off upon leak detection
VacTrain tunnel	Service tunnel	Electric wire over heating and short-circuiting	Aero-K system
	vacuum tunnel	vacuum pump overheating and thermo fluid leaks	Aero-K system
	Evacuation tunnel	N/A	Passive fire protection - fire protection boards, spray mortar protection, polypropylene fibers, fire safe concrete

Table 6 – Mitigation techniques for the VacTrain system

9.1 Alternative mitigation methods

As seen above the most feasible mitigation techniques have been recommended. The reasons for those specific mitigation techniques to be recommended are due to their application methods and their unique extinguishing characteristics. However the recommendations can be compared to other leading mitigation techniques in the industry and its advantages/disadvantages can be characterized as follows.

Suppression Systems	**Descriptions**	Advantages	**Disadvantages**
Aero-K[R]	The ultra-fine particulate comes in contact with the free radicals from the flames (oxidants), eventually preventing the propagation of the fire.	• Doesn't damage electrical components and it is non-corrosive • Specified for class C fires. • More effective than Halon and its repleacements. • Ecological friendly	• Not effective for fires of other classes • Activation has to be confirmed by two or three detectors • Dangerous in explosive atmospheres

		• Easy cleanup	
Micro-K	The combustion chain is broken by the aerosol particles. The particles are initially released by a generator to mix with the air. (Can be mechanically electrically or manually activated)	• Non-toxic and non-corrosive • Zero-ozone depletion potential • Efficient (small amounts required for large area) • Flexible release mechanism	• Dangerous in explosive atmospheres • Not specified for computer rooms
FireIce™	Rapidly cools and suffocates the fire, whilst making sure there are no relights from the remains.	• Ideal for direct suppression of structural fires and exposure protection • Non-toxic, non-corrosive • The cohesive layer formed, prolongs effectiveness of water • Ecologically friendly	• High cost • More commonly used for bush fires and wildfires
LPDF with Hypoxic Air	Utilized in commercial airline cargo holds.		
Novec 1230	Interrupts combustion chain reaction, cuts or dilute the source of oxygen, and remove heat from the flame.	• Zero ozone depletion potential • Applicable to class C fires • Rapid evaporation upon discharge • Designed for special hazards • Protects documents, antiques, other valuables • No post-fire residues	• High cost

Table 7 - Alternative mitigation methods

10 Recommended fire-safety features

After all the different sections of research have been complied together we are able to recommend a fire-safe design for the VacTrain. A purely conceptual transportation idea can be realized as seen below in its initial design stage.

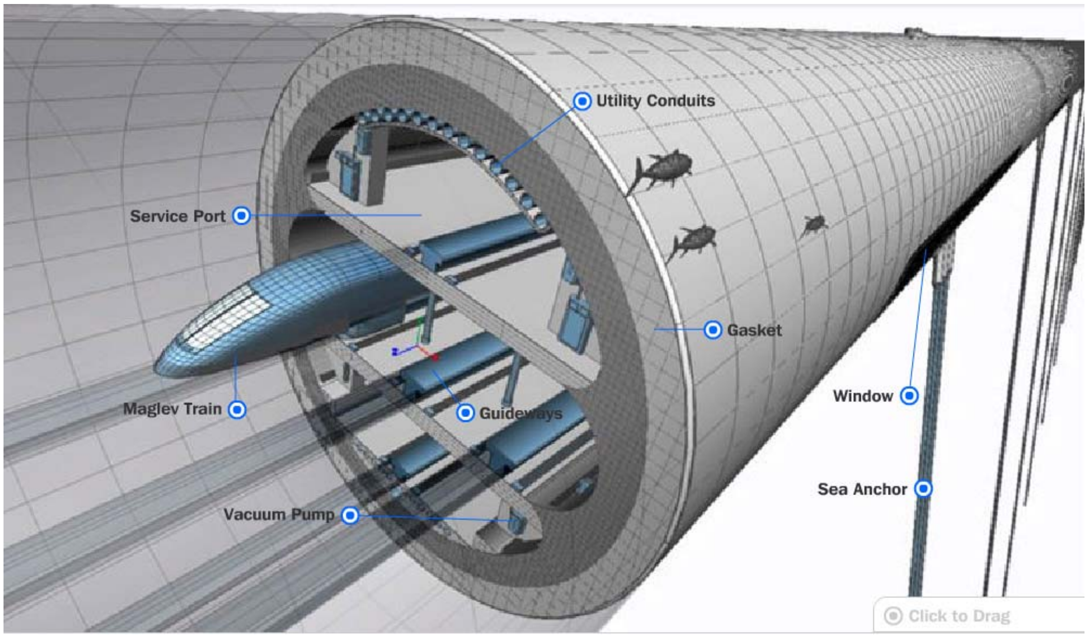


Figure 5 – VacTrain Design[1]

10.1 Recommended fire-safety features for the vacuum tunnel

The vacuum tunnel is made up of three shafts as seen from figure 6. The main shaft contains two magnetic tracks on which the Maglev will run on, in different directions. The shaft at the top of the main shaft serves as the maintenance tunnel used to repair and maintain the trains.

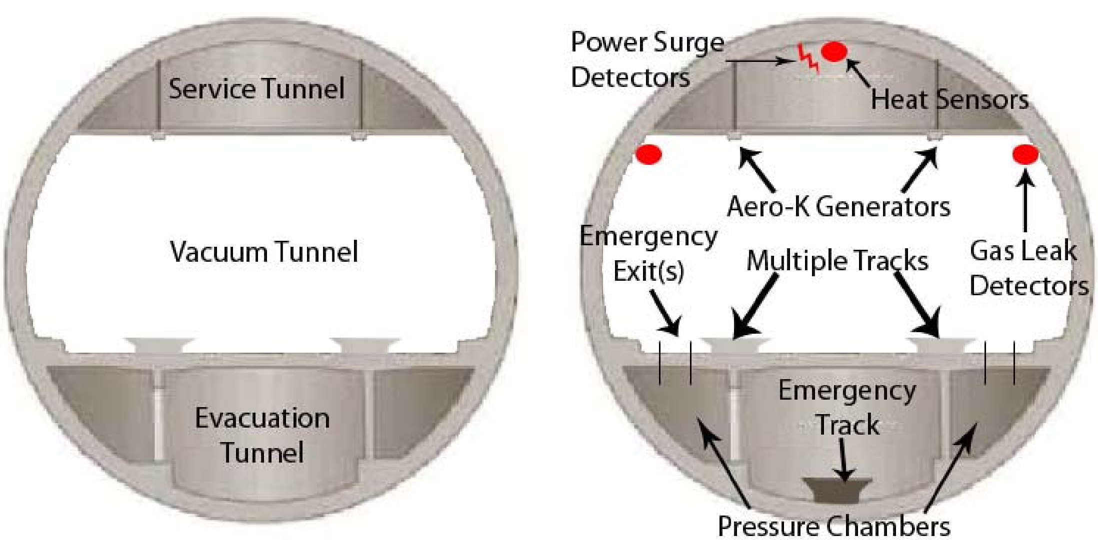


Figure 6 – Recommended fire-safety features for the tunnel design

The shaft at the bottom of the tunnel is the evacuation tunnel, used to evacuate passengers in case of emergencies; the shaft is equipped with magnetic tracks for another Maglev to evacuate the passengers to the nearest port.

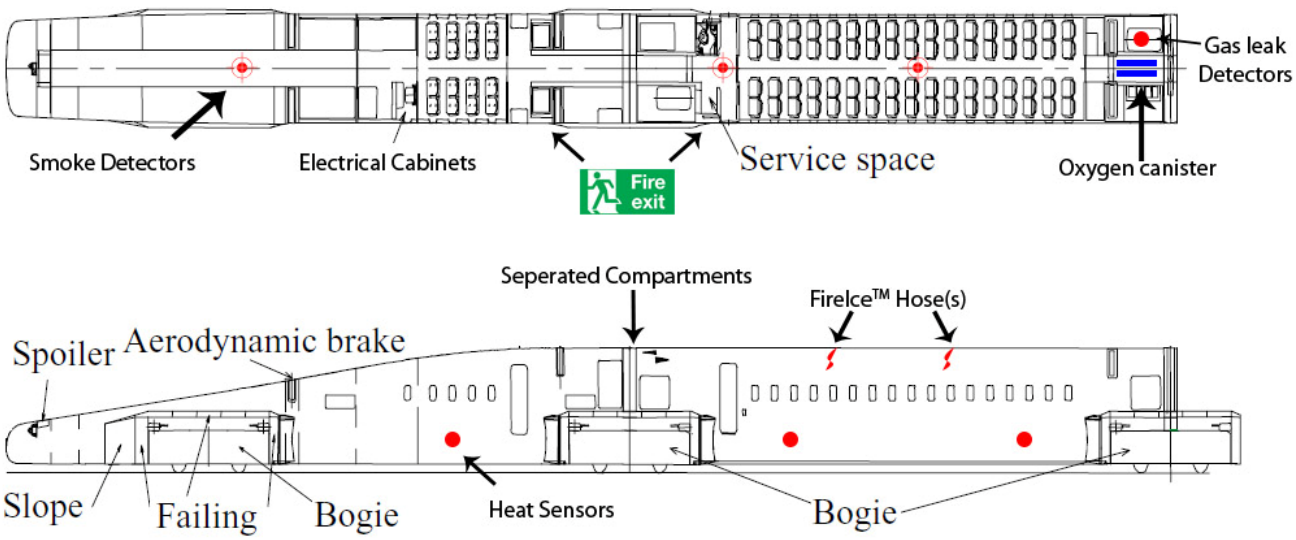
The most suitable fire suppression system to install within the vacuum tunnel is the new *Aero-K system*, which disperses ultra-fine potassium based aerosol[27] in the form of mist to combat the source of fire without damaging electrical hardware. This is an important aspect because the tunnel contains pertinent electrical components such as the magnetic tracks. The Aero-K system should be installed on the ceilings of the three different shafts of the tube; the main shaft, the maintenance shaft, as well as the evacuation shaft. The detection system most appropriate to trigger the Aero-K system is heat sensors installed on the walls of the tunnel, to detect abnormal temperature rises. These sensors should also be installed within the utility conduits where the electrical wirings are housed in as well as electrical cabinets (both in train and in tunnel); this will ensure detection of any overheated wires with the least amount of time. Power surge detectors should also be installed in the utility conduits to detect any electrical faults.

In addition to heat detection systems, there should be an emergency shutoff switch to shut down the power of the Maglev and the magnetic track in case of more severe emergencies; and another shutoff switch to cut all powers during maintenance and repairs.

The tunnel ceilings will have gas leak sensors to detect any leaks in the form of gas contaminating the vacuum tunnel; this will eliminate any possible sources that will ignite fire. The continuously running vacuum pump should pump out any impurities within tunnel. Furthermore, as indicated, there are exits available in the main tunnel that leads to the emergency tunnel.

[27] Periphman.com - Aerosol-fire-Suppression

10.2 Recommended fire-safety features for the Maglev train



[28]

Figure 7 – Recommended fire-safety features for the Maglev

The train designed to run within the vacuum tunnel is the aforementioned Maglev train. The fire detection and fire suppression features are as entailed in figure 7. At least two smoke detectors are to be installed within each compartment to ensure that any sources of smoke will be detected upon any fire breakout. Both the heat sensors and the smoke sensors will trigger the hoses equipped with the FireIce®[29] system, which is the most effective means of combating fire while preserving all the electrical hardware. Upon activating the system, the passengers should be evacuated from the compartment involved with the fire breakout. As mentioned before the heat sensors are also activated within the electrical cabinet, to detect any overheating in the electrical appliances. In addition to these systems, a gas leak detector should also be equipped within the vicinity of where the oxygen canisters are, to detect any leaks from the canister, as they are dangerous sources of ignition.

[28] Improving Maglev Vehicle Characteristics for the Yamanashi Test Line by Katsuya Yamamoto, Yuichi Kozuma, Naoto Tagawa.
[29] Fireice - GelTech Solutions, Inc.

10.3 Special case scenario

Since the Maglev train runs in a vacuum environment, it is always prone to being exposed to the vacuum tube. In case of a breach in the Train out shell, there will be a cabin pressure drop. This could also happen due to a fire Hazard scenario, where the passengers will need additional Oxygen. In these types of special scenarios the Train design will be equipped with the ventilation system[30] shown in Figure 8.

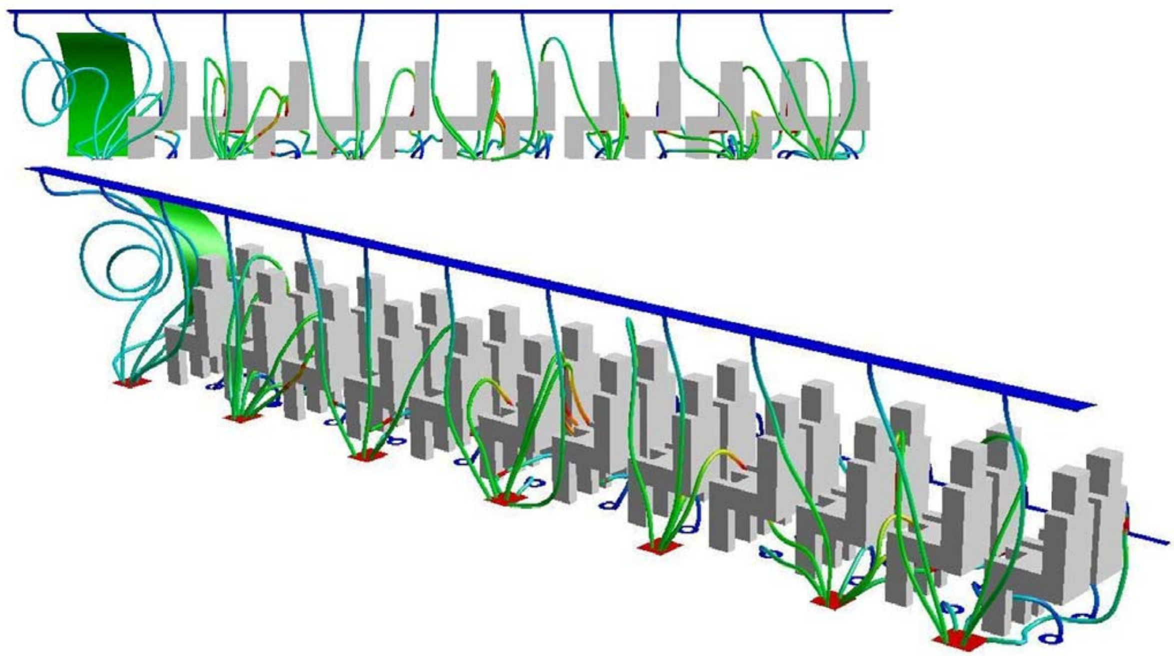


Figure 8 – Oxygen system in case of emergency

[30] GLOBAL MODELISATION OF THE SWISSMETRO MAGLEV USING A NUMERICAL PLATFORM by Prof. Marcel Jufer, Dr Vincent Bourquin, Dr Mark Sawley

11 Conclusion

The VacTrain is a revolutionary concept in transportation technology that has been around since the early 1900s. However, as previously mentioned in the report, it has its share of fire hazards. Furthermore, there has never been a report that goes as far as to present the fire hazards related to its conceptual design. By analyzing the fire hazards related to train systems, tunnels and other industries related to this concept, this report presents an educated analysis of the possible fire hazards within the system. The collective outcome of this report is a recommendation of fire-safe features to be equipped in the system that will successfully prevent and suppress any fires in the system.

After analyzing and comparing the different fire hazards and fire-safety features of different train systems, it is observed that some similar hazards might arise in the VacTrain. Therefore similar evacuation and suppression techniques can be extracted from these related systems and applied to the VacTrain. However since the VacTrain is electrically operated, the fire-hazards of the electrical components are relevant to the fire-safe VacTrain design. Some recommended fire-safe features that can be derived from the comparison are the gaseous fire suppression systems and the emergency switch that would shut-off the system during emergencies.

Analysis of the maglev train proved to be very helpful in making predictions for this fire-safe VacTrain. Concepts on evacuation and suppression were taken from studies done on the Munich trans-rapid and recommendations were laid out in terms of docking stations, exit strategies and evacuation procedures for passengers.

The power consumption of this train system proves to be very high due to the use of vast amounts of electrical components; such as the Induc-Track, Vacuum pumps etc. This poses another threat to the safety of the train because of short-circuiting and or overheating in the wiring. Early detection systems like optical smoke sensors and heat sensors are recommended accordingly.

Since there hasn't been any fire hazard analysis made on the VacTrain, the only way to obtain the fireload data was by analyzing a similar system. Given the similarity of the VacTrain and commercial airline cabins, assumptions were made to measure the fireload onboard an airplane cabin. This comparison was made based on the rate of combustion of materials available onboard of a Boeing 747-400. The weight of the fuel, which contributes to a big part of the calculation for an airline, was deemed irrelevant in estimating the fireload for the VacTrain. Instead, factors like oxygen canisters and flammable cargo materials were taken into account. Based on this fireload analysis and their flammability rates, composites like PVF-phenolic/epoxy or glass were recommended for the interior make up of the cabin.

Many conclusions were made with relevance to studies of other tunnel systems. Wire coverings, optical smoke and heat detectors for the wires that run through the tunnel appeared very necessary for a safe system. Concepts like the use of service and evacuation tunnels were validated because of their usefulness during any kind of hazard. Readily available vacuum pumps proved to be very important to avoid contamination of the vacuum environment by any kinds of gases from peripheral environments.

Incidents in other underwater transports like submarines helped to conclude that the use of carbon dioxide suppressants might be very harmful to the occupants in a closed environment. Therefore, other novelty non toxic suppressants like the Aero-k® and FireICE™ were recommended.

Accounting all these factors, the recommended fire-safe features were detailed in this report. It can be said with the use of all these recommended mechanisms and techniques, the VacTrain will not only be one of the fastest and most economic mean of transportation but it will also be a fire-safe transportation system. Combining the economical feasibility study in the previous project with the fire hazard analysis associated with the VacTrain, this concept is drawing closer to its realization.

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