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INTEGRATION AND PERFORMANCE STUDY OF VACUUM PUMPS AND AIRLOCKS IN A HYPERLOOP SYSTEM

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Integration and Performance Study of Vacuum Pumps and Airlocks in a Hyperloop System

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Abstract

Hyperloop transportation requires a reliable vacuum pump and airlock system to main its near-vacuum environment. This study investigates the efficiency of current vacuum pump technology, specifically gas displacement pumps, and different concepts of airlocks. The pumps studied in this paper include roots pumps, rotary vane pumps and liquid ring pumps, while the airlocks discussed are single air chamber, end-door airlocks, bridge doors airlocks and twin airlock chambers. These technologies are technically analysed and evaluated for their use in a hyperloop system. Through comparison, it was found that the most efficient system using these technologies would be a combination of roots pumps, backed by rotary vane pumps, in an end-door airlocks system. Lastly, this paper investigates methods to manage the vacuum level within a hyperloop tube in terms of monitoring, maintaining and mitigating leaks.

1 Introduction

The near-vacuum environment in a hyperloop tube is one of the most crucial aspects of an efficient hyperloop system. As a result, vacuum pumps and airlock systems have become a common topic in the development of a successful implementation of a hyperloop system.

The primary objective of this study is to analyse and determine possible methods and modifications to optimise the performance of vacuum pumps and airlocks when being implemented in a hyperloop system. Through literature review, various vacuum pump technologies, including roots pumps, rotary vane pumps and liquid ring pumps, are evaluated in terms of their suitability for achieving the required vacuum levels and their efficiency in maintaining them. The advantages and weaknesses of each pump are discussed, which allows for a comparison between the pumps to determine which pump is the most suited for a hyperloop system. In addition to this, vacuum management is discussed to determine efficient ways to monitor and maintain a near-vacuum environment in a hyperloop tube. This discussion also includes studying multiple sources of leakage which would lead to the failure of the vacuum and the corresponding solutions to mitigate these sources.

Furthermore, this paper also investigates different types of airlock systems and their characteristics. The advantages and disadvantages of these airlocks are deduced based on several considerations, such as spatial requirements, safety features, access control, and maintenance. Airlock technology in the hyperloop industry is still relatively new, and hence, the paper visualises the airlock concepts for a hyperloop system and provides recommendations on how the current concepts could be modified for better performance.

Overall, this paper aims to provide valuable findings that can contribute to the advancement of vacuum pump and airlock technologies for a hyperloop system. Through a deeper understanding of different pump technologies and airlocks systems, it becomes more possible to engineer reliable hyperloop systems and reshape the future of transportation.

2 Vacuum Pumps

In a hyperloop system, the main purpose of vacuum pumps is to remove gas molecules from the tube to create either a near-vacuum or a very low-pressure atmosphere. By utilising vacuum pumps to manipulate the pressure within the tube, air resistance within the tube can be significantly reduced, allowing the pods to move at ideal high speeds. To implement vacuum pumps in a hyperloop system, they need to meet a series of requirements. The pumps need to be able to extract a significant volume of gas molecules while simultaneously maintaining a consistent low pressure environment. Additionally, for optimal performance, the pump should have high pumping speeds and be designed to be energy efficient to minimise power consumption.

2.1 Types of Vacuum Pumps

Currently, there are multiple types of vacuum pumps available on the market, each employing different mechanisms to remove gas molecules. The decision on what pump to use depends on the requirements of the application of the pump, such as the desired vacuum level, the gas composition of the environment of the application, and the pumping speed. Hence, each type of vacuum pump has its own specific benefits depending on its intended application.

Overall, vacuum pumps are divided into two main types: gas transfer and gas binding vacuum pumps as shown in Figure 1. Gas transfer vacuum pumps extract gas particles from the environment and eject them to the atmosphere, external to the volume being pumped. This operation may be achieved through either a single or multiple compression stages. Gas transfer vacuum pumps can be further categorised into two types depending on how the gas is transferred. Kinetic pumps eject gas molecules by propelling the molecules in the pumping direction, either through a mechanical drive system or by utilising condensation of a vapor stream, directing it out of the pump. Positive displacement pumps remove gas molecules from a sealed volume either to the atmosphere or downstream of the pump. In contrast, gas-binding vacuum pumps remove gas molecules chemically by binding the molecules to an active substrate by bonding or condensing the gas at a specific temperature. Hence, a gas binding vacuum pump is also termed as an entrapment vacuum pump [23].

The pumps analysed in this paper are gas transfer pumps, gas binding pumps will not be discussed as they have a limitation to their gas adsorption capability, and hence, require maintenance at certain intervals of the process, depending on the intensity with which the pump is used, which is not ideal for a hyperloop system. The gas pumps covered by this paper will be analysed in terms of their mechanism, advantages, disadvantages, and how efficient their operation would be in a hyperloop system. Due to the scarcity of publicly available information, an economic analysis was not undertaken for these pumps. Additionally, this study will also discuss potential methods on how the pressure within the tube of a hyperloop system can be monitored and maintained. Leakage is a common major issue with maintaining vacuum levels, and the sources of this issue will be investigated, along with their corresponding mitigation methods. Finally, since being in a vacuum can be harmful to humans, the last section will discuss safety regulations and procedures to handling vacuums considering passengers' health and safety.

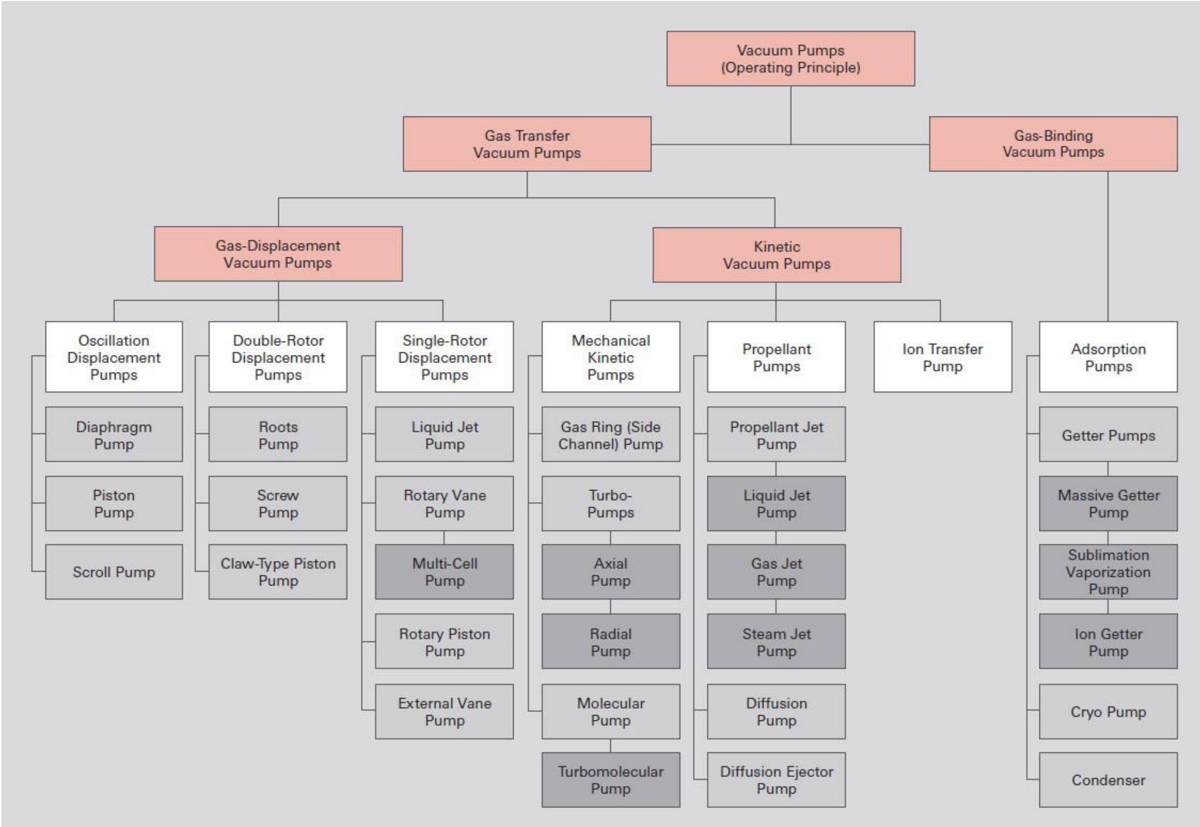

Figure 1: Overview of Vacuum Pumps [1]

The vacuum pumps covered by this paper fall are roots pump, rotary vane pump, and liquid ring pump, which are gas displacement pumps. The paper primarily focuses on gas displacement pumps because they are the dominant vacuum pump in the global market due to a wider range of available designs, and hence, they can be utilised across different industries from the medical to the scientific sector. Furthermore, while entrapment vacuum pumps are known to be very effective in achieving ultra high vacuum levels, this performance comes at a high cost and requires frequent regeneration as more gas molecules are trapped by the surface. Hence, this makes their operational time very short, turning them extremely inefficient for a hyperloop system, where the vacuum level of the tube needs to be maintained continuously and at a low cost.

2.2 Roots Pump

2.2.1 Mechanism

A roots pump consists of two parallel, interlocking rotors known as the male and female rotors labelled as number 4 in Figure 2. These rotors are uniquely shaped, resembling figure-eight lobes. Encased within a housing, the rotors rotate in opposite directions while maintaining synchronous motion [28]. As the rotors turn, a series of air pockets form between the lobes and the pump housing which is called a suction chamber, indicated as number 8 in Figure 1. This air pockets' movement from the inlet to the outlet side of the pump facilitates the transfer of air and the creation of a pressure difference, resulting in the generation of a vacuum [29].

The synchronous rotation of the male and female rotors is a crucial aspect of the roots pump's mechanism. The interlocking design ensures that the rotors do not come into direct contact, eliminating the need for internal sealing [28]. Instead, the gas is trapped within the spaces formed by the rotor piston and the pump housing as shown in Figure 2. The synchronous rotation of the rotors carries the air pockets along, allowing for continuous movement and transfer of gas through the pump [30].

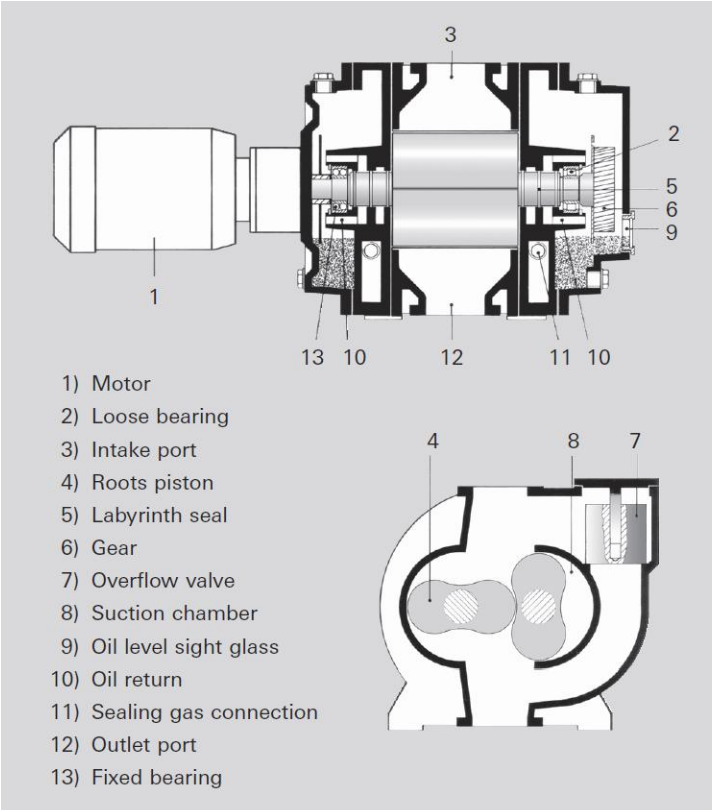

Figure 2: Root Pump Inner and Outer Structure [2]

While there is no internal sealing, maintaining minimal gas leakage is essential for the efficient operation of the roots pump. To achieve this, close tolerances and external sealing mechanisms are employed. External sealing often involves the use of sealing glands or O-rings to limit gas leakage and optimise the pumping action [31]. The roots pump can create and sustain a vacuum by implementing adequate sealing and precise clearances.

As the air pockets progress from the inlet to the outlet side of the roots pump, the gas is transferred and compressed. The trapped air undergoes isochoric compression, where no internal volume reduction takes place [32]. The compressed gas is then discharged through the outlet port, while fresh gas continuously enters the pump through the inlet port, enabling the cyclical process to continue [30].

Roots pumps are also a type of positive displacement pump that operates without internal compression. This characteristic implies that they are unable to directly compress gases to atmospheric pressure, which will be essential in the docking section of the track tube. Instead, they are typically used in conjunction with a fore vacuum pump to achieve the desired pressure level by further compressing the gas [28].

2.2.2 Advantages

Utilising roots pumps for a hyperloop track system presents several advantages and disadvantages. First and foremost, roots pumps excel in generating a vacuum swiftly. Their high pumping speed (may reach over 100,000 m^3/h with an assembly of units) allows for the rapid removal of air from the track tube, establishing a low-pressure environment essential for achieving optimal performance [28]. This efficiency in vacuum generation significantly reduces air resistance, enabling the pod to attain remarkable speeds.

Furthermore, roots pumps are renowned for their reliability and ability to operate continuously over extended periods, commonly having a service life of 20,000 hours without the need for maintenance [33]. They have no contact between meshing lobes and rotor casing, hence roots pumps are less probable for mechanical wear from shear stress [30]. Their durable construction ensures consistent operation, minimising interruptions and downtime in the hyperloop system [29]. Such reliability is imperative for maintaining a seamless transportation experience, as any disruptions or breakdowns can lead to significant delays and inconvenience for passengers.

Roots pumps also count with exceptional pressure recovery capabilities due to their impressively high pumping speed within the range of 25 to 200 m^3/h [29]. If there are any disruptions or changes in pressure occurring within the track tube, roots pumps can swiftly restore the vacuum level to the desired state. This capability optimises the energy efficiency of the transportation system by reducing the need for additional energy input to compensate for pressure variations.

2.2.3 Disadvantages

It is important to consider the disadvantages associated with roots pumps in a hyperloop track system. One notable drawback is the risk of backstreaming. Roots pumps are sensitive to the backflow of gas from the outlet side to the inlet side, which can reintroduce air into the tube, compromising the vacuum level and increasing air resistance. Gas backflow may negatively affect the compression ratio of the pumps, which will then impede the pump's overall performance and efficiency [2].

Implementing preventive measures such as the use of check valves or traps as indicated in Figure 3 is imperative to mitigate the potential for backstreaming. Without a check valve in place, there is a possibility of the air in the pump chamber returning back to the vacuum system [34]. This is undesirable as it can lead to a loss of vacuum or contamination of the pumped environment. To prevent gas backflow, a check valve, also known as a one-way valve, is installed at the air inlet. The valve ensures that the air in the pump chamber cannot be pushed back into the pumped container [34]. The reverse flow of air is properly blocked by closing the check valve before stopping the roots vacuum pump. It maintains the pressure difference between the exhaust port and the air inlet, ensuring that any residual pressure in the pump chamber does not compromise the vacuum system or introduce unwanted substances into the pumped environment. The addition of a check valve at the air inlet serves as a preventive measure to safeguard the integrity and functionality of the vacuum system.

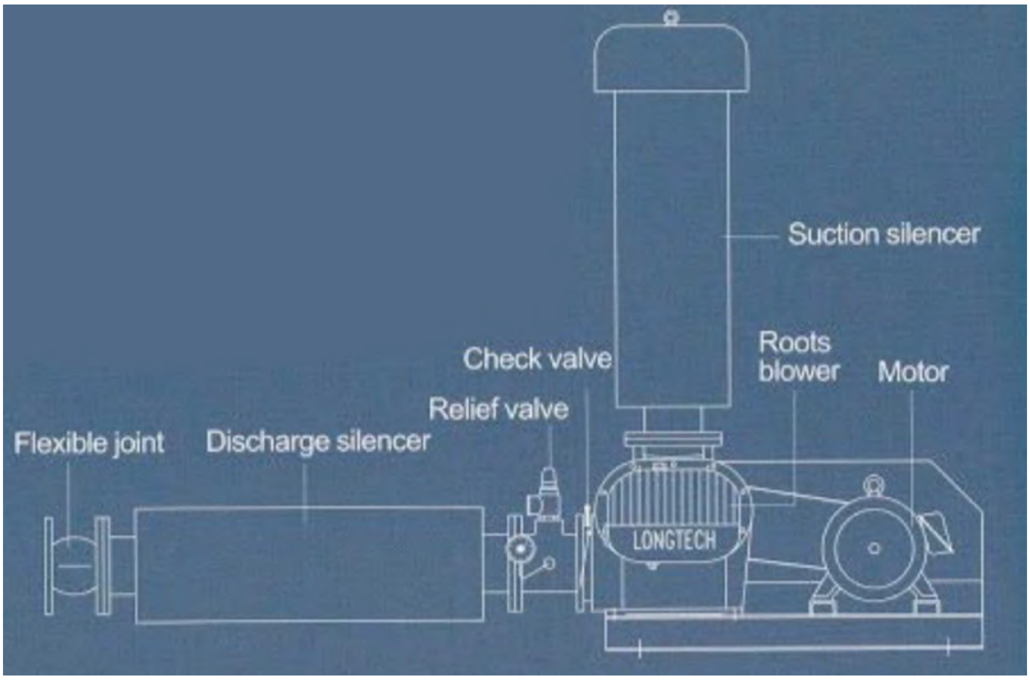

Figure 3: Check Valve Implementation on Roots Pump [3]

Another limitation is the relatively low compression ratio of roots pumps compared to other vacuum pump types. Low compression ratio leads to roots pumps' high pumping speed, therefore it is important to consider the trade-offs between these two criteria. While the low compression ratio can be seen as a disadvantage in certain applications that require a high compression ratio, it can be advantageous in other scenarios where it is not a critical factor. Different applications may prioritise one characteristic over the other, highlighting the need to carefully assess the trade-offs and select the most appropriate pump for the desired outcome.

While roots pumps are suitable for creating low-pressure environments in hyperloop systems, achieving extremely high vacuum levels may necessitate the inclusion of additional vacuum stages or alternative pump types. Besides this, they are typically not designed to be started directly under normal pressure conditions. This could lead to an increased usage of motor power, which could impact the efficiency of the pump in the long run. With the aid of a backing pump, such as a rotary vane pump, the roots pump can have a smoother start-up, which will then elongate its overall shelf life. Also, the performance characteristics of the roots pump can be fully utilised with a backing pump [35].

Lubrication and maintenance requirements are also worth considering. Although the suction chamber is not oil-sealed [28], lubrication in the roots pump is confined to the two bearings and gear chambers shown in Figure 2, situated outside of the suction vessel to reduce friction that could lead to wear and tear [36]. These components are effectively separated from the gas suction cavity by utilising labyrinth seals equipped with compression rings [2]. An initial oil change is recommended after approximately 500 hours of service to eliminate any metal particles generated during the initial period. Subsequently, changing the oil every 3000 hours is sufficient for routine operation. However, in environments with dust or other contaminants, more frequent oil changes are necessary [33]. Adequately containing the lubricating oil is crucial to prevent contamination in the track tube and associated components.According to a survey done by supervacindustries shown in Figure 4, 89% of issues with roots pumps are directly related to lubrication [4]. Simply selecting a high-quality pump is insufficient. To maximize the pump's value, it must be operated with the correct oil and regular, timely oil refills must be ensured.

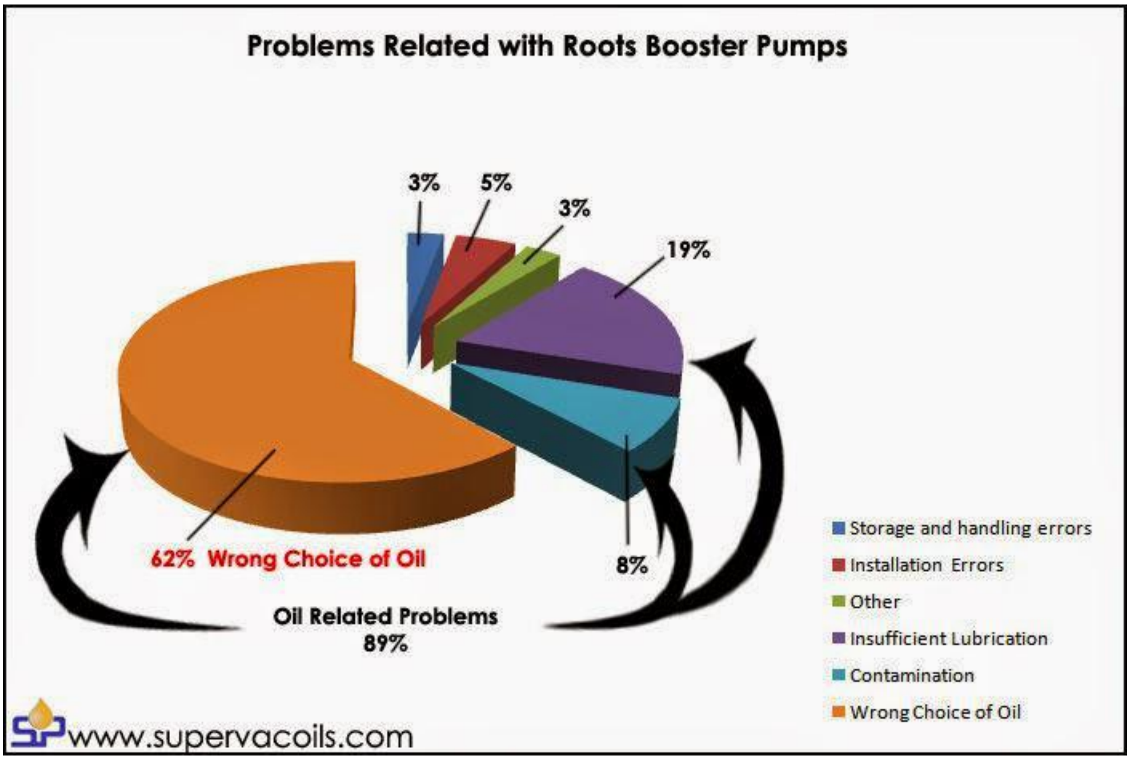

Figure 4: Survey on Problems Related with Roots Pumps [4]

Regular maintenance is needed for root pumps to ensure optimal operation. To maintain a roots pump, begin by disconnecting the two connection pipes and perform a thorough flushing of the system using dry compressed air or an appropriate cleaning agent. It is necessary to replace the oil in the pump as part of the cleaning process. During cleansing, ensure that the rotor is manipulated manually to prevent any damage. Stubborn dirt and grime can be eradicated using tools such as a bristle brush or scraper. After purging, it is vital to assess the pump's functionality by verifying the smooth rotation of the rotor. In the case of significant contamination taking place, professional assistance from manufacturer may be required [33].

Although roots vacuum pumps, or booster pumps, are known for their low noise and stable high vacuum performance, there can still be instances of unusual noise during operation. Factors such as unlevel mounting surfaces, deformation of the cooling fan, bearing issues and friction and wear of internal components contribute to the overall noise level [37]. It is important to address these noise concerns, especially in a hyperloop system where noise impact on the surrounding environment is a significant consideration. Implementing noise reduction measures such as enclosures or silencers becomes crucial to minimize noise and vibrations. By effectively reducing these, the system can mitigate disturbances in the surrounding areas and ensure a more harmonious integration with the environment [36].

2.3 Rotary Vane Pump

2.3.1 Mechanism

A rotary vane pump is a positive displacement pump that operates based on the sliding motion of vanes within radial slots. As shown in Figure 5, a single stage pump consists of a cylindrical rotor with multiple vanes inserted into these slots. The rotor is eccentrically mounted within a larger housing, creating crescent-shaped cavities between the vanes and the casing.

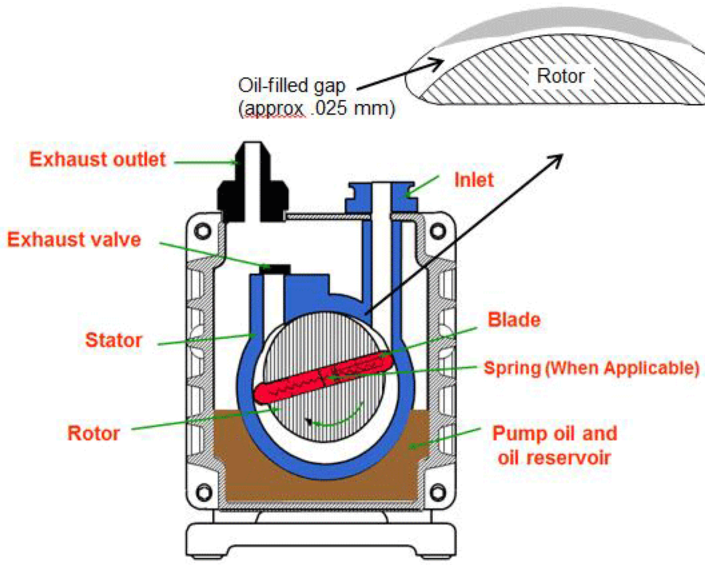

Figure 5: Cross-sectional view of a rotary vane pump [5]

During operation, fluid or gas enters the pump through the inlet port. As the rotor spins, the vanes slide in and out due to the centrifugal force and contact with the housing wall. As the vanes make contact with the chamber wall, they trap a volume of gas between them. As the rotor continues to turn, the vanes move away from the chamber wall, causing the trapped gas volume to increase. This expansion of the cavity reduces the pressure within the chamber, creating a partial vacuum.

The trapped gas is carried around the casing until it reaches the discharge port. As the gas passes through the pump, it undergoes compression due to the decreasing volume of the crescent-shaped cavity formed between the vanes and the casing. The fixed volume of this cavity leads to the compression of the gas.

Once the gas is sufficiently compressed and the chamber reaches the outlet port, it is expelled from the pump at a higher pressure. The expelled gas then flows out of the pump, while fresh gas or fluid is continuously drawn into the inlet port to maintain the cycle. This process of trapping, compressing, and expelling gas enables the rotary vane pump to effectively generate and sustain a vacuum.

Rotary vane pumps can also be made up of multiple stages such as the two-stage pump shown in Figure 7. In contrast to the single-stage rotary vane pump, a multi-stage rotary vane pump incorporates multiple stages to achieve higher vacuum levels. Each stage consists of a vanes, a working chamber, and a rotor as mentioned previously. The gas is compressed and transferred through a series of stages, with each stage further reducing the pressure. As the gas moves from one stage to the next, it undergoes additional compression, resulting in a more refined vacuum. This sequential compression process allows the multi-stage rotary vane pump to achieve lower ultimate pressures compared to a single-stage pump. The utilization of multiple stages enhances the pump's performance and efficiency, making it well-suited for applications that require higher vacuum levels. Rotary vane vacuum pumps and systems can be designed with one or more stages to create a vacuum. Each stage consists of essential components like the working chamber, rotor, and vanes. In various applications, including hyperloop, multistage pumps tend to offer higher efficiency compared to using separate pumps in series.

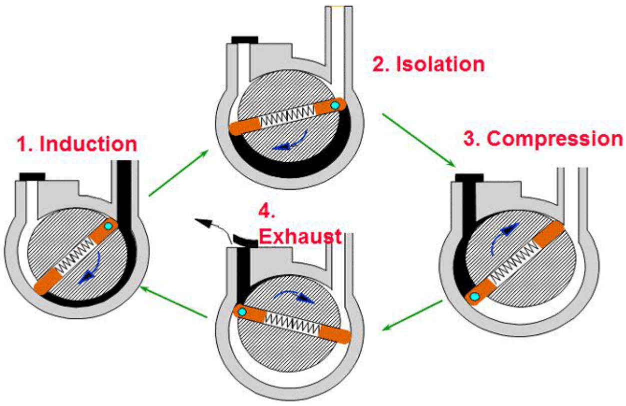

Figure 6: Four stages of a rotary vane pump [6]

The most common rotary vane vacuum pumps are single-stage pumps, where gas molecules are directly moved from the evacuated chamber into the atmosphere. These pumps achieve ultimate pressures of around 10 millibar. However, there are two-stage rotary vane pumps available that evacuate gas molecules in two stages, allowing for lower ultimate pressures reaching up to 1 millibar. Although not as common, there are also three-stage rotary vane pumps that can reach further increased ultimate vacuum levels. Three-stage pumps can involve the combination of a one or two-stage rotary vane pump with another pump type. Additionally, systems utilizing rotary vane pumps with four or more stages typically feature a combination of a one or two-stage rotary vane pump with other pump types. These multi-stage and pump combination setups are employed in applications that demand extremely high vacuums, which is recommended for hyperloop applications. For example, the pump system combination of the high pumping speed of the rotary vane pump and the oil-free advantage of a diaphragm pump would combine the positive characteristics of the different pumps resulting in a more beneficial system [38].

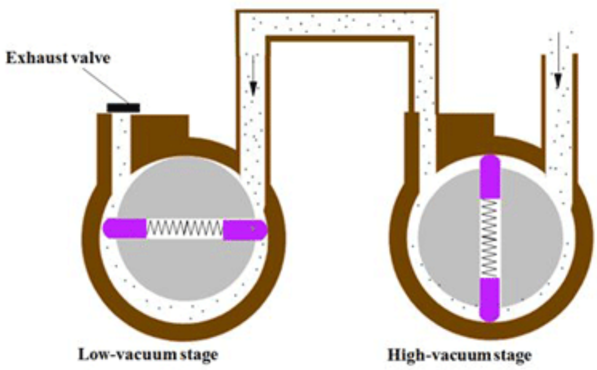

Figure 7: Two-stage rotary vane pump concept [6]

2.3.2 Advantages

One of the advantages of rotary vane pumps is the minimal metal-to-metal contact inside the pump. The vanes, typically made of carbon graphite, eliminate the need for direct metal contact, reducing wear and tear on the internal components [39]. This not only lowers maintenance requirements but also provides good efficiency [40]. The pressure ranges of rotary vane pumps vary based on the specific model and design. Leybold, a manufacturer of rotary vane pumps, offers different ranges of pumps that are tailored to meet the requirements of various applications.

Table 1: Pressure Ranges for Different Vacuum Levels [23, 24]

Vacuum state	**Pressure range in millibar (mbar)**
Rough vacuum	10^3 to 1
Medium vacuum	1 to 10^{-3}
High vacuum	10^{-3} to 10^{-7}
Ultra high vacuum	10^{-7} to 10^{-12}
Extreme high vacuum	less than 10^{-12}

It is difficult to comment on the overall vacuum levels that rotary vane pumps can reach as this depends hugely on the stage-type of the pump chosen. In general, as the number of stages increases in a rotary vane pump, the pumping efficiency of a multi-stage system tends to improve, and the ultimate vacuum level achievable becomes lower. However, it is important to note that increasing the number of stages also typically results in higher manufacturing costs and a larger physical size of the pump. Therefore although rotary vane pumps can theoretically reach a high vacuum level, there may not be the space available to accommodate the size of the pump required to do so. Generally, the compact and space-efficient design of rotary vane pumps would make them well-suited for installation in hyperloop systems with limited space, especially if the system were to be built underground. However, this typically refers to single-stage pumps. There is a payoff between size and vacuum level to be achieved for rotary vane pumps of higher stages.

In a hyperloop system, despite rotary vane pumps generally being able to provide a low pressure, a multi-stage vacuum pumping setup would be most suitable. As mentioned previously, a combination of different types of pumps would combine their advantages such as lack of dependency on oil, lower pressure achievability, and negate the disadvantages. Different pumps in series, potentially ion pumps or turbomolecular pumps alongside rotary vane pumps, will help to provide the desired low-pressure levels at higher pumping speeds.

One of Leybold's notable rotary vane pump ranges is the TRIVAC series [41]. These pumps are available as two-stage pumps, referred to as TRIVAC D pumps. The two-stage design allows for lower operating and ultimate pressures compared to single-stage pumps. In single-stage pumps, the presence of oil in contact with the atmosphere outside can lead to the intake of gas, which partially escapes to the vacuum side and limits the achievable ultimate pressure. The oil-sealed two-stage displacement pumps by Leybold are designed to address this limitation. Degassed oil is supplied to the vacuum side stage (stage 1). As a result, the ultimate pressure of the pump is significantly improved, reaching the high vacuum range. The lowest operating pressures of these pumps typically lie in the range between medium vacuum and high vacuum, according to Table 1.

It is important to note that operating the high vacuum stage (stage 1) with minimal or no oil can cause significant difficulties and impair the pump's operation, despite the potential for achieving very low ultimate pressures. Maintaining the appropriate oil level is crucial for proper functioning and optimal performance of the pump, which is a disadvantage compared to oil free pump mechanisms. Whilst it is possible for a rotary vane pump to run dry for short periods of time if needed, it should not be done regularly.

Generally, rotary vane pumps are capable of achieving high pumping speeds; Leybold's SOGEVAC BI pump can reach a pumping speed of 147 m^3/h. The high pumping speed allows rotary vane vacuum pumps to quickly reduce the pressure inside the pod to the desired level, allowing for efficient operation of the hyperloop system. However, despite their high pumping speeds, they do not seem to be enough to support the vacuum requirements of the hyperloop alone. The Leybold's website itself states the "TRIVAC B pumps, used to generate a rough and medium vacuum or as backing pumps in pump combinations with Roots vacuum pumps or high vacuum pumps" [41] showing that manufacturers themselves do not consider these pumps to be sufficient for high vacuum purposes alone, despite there efficiency. Rotary vane pumps are reliable and have long operational lifespan. These properties help to reduce system downtime and minimises the risk of unexpected failures or maintenance requirements.

2.3.3 Disadvantages

The main disadvantage of rotary vane pumps seems to be that rotary vane pumps alone will not be sufficient to maintain a vacuum appropriate for hyperloop's purposes [6]. Although commonly used in industry, rotary vane pumps are also referred to as a "backing" pump. This is when used in combination with other pumps such as booster pumps and/or with a second higher pressure pump. Rotary vane pumps can be used alone, but this is typically only when a high vacuum is not required and a slower pump-down is acceptable. Both of these traits, however, are quite important for hyperloop use.

While it is not as relevant for the particular purpose of hyperloop, a common advantage given for rotary vane pumps is their efficiency in dealing with a wide range of fluids of varying viscosities. In hyperloop, the primary fluid dealt with would be air, but this does provide flexibility with the maintenance oil used and potential changes in the atmosphere and weather along the journey.

Minimising noise produced by hyperloop is important for various reasons. Quieter running will prevent disturbances to the environment including any wildlife or people living near the track. Excessive noise can disrupt wildlife and noise pollution from transportation systems can lead to annoyance and sleep disturbances for nearby residents. Furthermore, addressing noise concerns early in the process can help in gaining public acceptance and support for the adoption of hyperloop as a public transportation system as noise is a common concern for communities when large-scale infrastructure projects are proposed. Quieter running will also contribute to efficient functioning of hyperloop systems as less energy is wasted to sound. Rotary vane vacuum pumps, are known for their quieter running which can help to maintain a quiet and comfortable environment for passengers if used [42,43].

Although rotary vane pumps have the advantage of being quieter compared to some other pump types, sitting around 65 decibels, they still produce some noise and vibration during operation. In his paper analysing vibration for predictive maintenance of a rotary pump, Osswald revealed in his preliminary test results that vibrations induced by cavitation in these pumps are significantly stronger than those experienced during normal operating conditions, particularly for speeds ranging from 50 to 200 rpm [44]. These intense vibrations can have adverse effects on the pump's components, potentially leading to increased wear and reduced lifespan. To mitigate these issues, it is important to implement measures that minimize cavitation-induced vibrations. Additionally, careful design considerations, such as selecting optimal positions for accelerometers and utilizing high-pass filters, can help identify and analyze the high-frequency noise associated with cavitation. By understanding and addressing vibration levels, hyperloop developers can ensure the durability and reliability of rotary vane vacuum pumps, contributing to the long-term success of the transportation system. Comparing the vibration levels of rotary vane pumps to other vacuum pumps, literature does not indicate any profound difference in vibration levels. Therefore any limitations arising from the vibrations, such as increasing wear, affect all pumps and not just rotary vane pumps.

Rotary vane pumps are also known for their ability to generate smooth and consistent flow rates. This characteristic is particularly advantageous for hyperloop vacuum systems, as it ensures stable and reliable operation. This increases efficiency and allows for less frequent maintenance.

The most common disadvantage research shows for rotary vane pumps is their reliance on oil [45]. Firstly, the use of oil in rotary vane pumps can introduce the risk of oil contamination. In certain applications where a clean and oil-free environment is critical, such as in semiconductor manufacturing or medical devices, the presence of oil particles can be detrimental to the process or product. Secondly, regular maintenance is necessary to monitor and replace the oil in the pump. Oil changes, filter replacements, and proper disposal of used oil are essential tasks to ensure the pump operates at its optimal efficiency.

Neglecting oil maintenance can lead to decreased performance, increased energy consumption, or even potential pump failure. Furthermore, oil lubrication in rotary vane pumps may pose environmental concerns. Improper disposal or accidental oil leaks can harm the environment and necessitate careful handling and proper waste management practices.

Proper maintenance is vital for ensuring the longevity and optimal performance of rotary vane pumps. Regular maintenance procedures help prevent potential issues, optimize pump efficiency, and minimize downtime. Some of the key aspects of oil maintenance are as follows [46, 47]:

- Oil Change: Timely replacement of oil is crucial for rotary vane pumps. Like car engines, the industry standard for maximum usage between oil changes is 3000 hours. For a pump running 24/7 this is approximately 4 months, although the exact frequency between changes will depend on the specific manufacturer and pump usage. The oil lubricates the pump, ensuring smooth operation and effective sealing. Regular oil changes are necessary to maintain pump efficiency and prevent detrimental effects on the vacuum system.
- Component Inspection and Replacement: Worn or damaged components, including vanes, seals, and filters, should be regularly inspected. Worn vanes can reduce pumping efficiency and compromise vacuum levels, while damaged seals can cause air leaks and a loss of vacuum integrity. Proactive replacement of these components ensures optimal pump performance and reliability.
- Cleaning: Keeping the pump clean and free from debris is essential. Regular cleaning of the pump's exterior and intake filters prevents the accumulation of dirt and particles that can hinder performance or cause damage. Specific cleaning procedures will be given by specific manufacturers.
- Record Keeping: Maintaining comprehensive records of maintenance activities and pump performance is crucial. These records facilitate effective troubleshooting, track the pump's health over time, and help identify recurring issues. They also aid in determining appropriate maintenance intervals and predicting potential failures or the need for pump replacement.
- Downtime Reduction: Efficient scheduling of maintenance tasks is essential to minimize downtime. For a hyperloop system, maintenance should be during periods of planned downtime or low public demand, such as at night and other off-peak travel times, to minimize the overall disturbance. Proactive maintenance practices and well-planned schedules help reduce the downtime of rotary vane pumps and ensure a reliable and efficient vacuum system. Having a backup pump available is also recommended to further minimize downtime. In the event of pump failure, a backup pump allows for quick replacement and uninterrupted operation.

In addition, keeping thorough records of past maintenance and pump performance will allow the pump's health to be tracked over time. This will aid in determining appropriate maintenance intervals and predicting potential failures or maintenance requirements. By adhering to these maintenance practices, the longevity, reliability, and performance of the rotary vane pump system should be enhanced and maintained.

Rotary vane pumps offer several advantages as vacuum pumps, including efficient vacuum generation and reliability [38, 48]. However, they do have limitations, especially when dealing with condensable vapors and have the potential for backstreaming oil contamination.

To address these challenges and combine the benefits of different pump types, a solution can be found by utilizing a combination of diaphragm pumps, rotary vane pumps, and/or roots pumps in series. By connecting these pumps, we can capitalize on their individual strengths and mitigate their weaknesses. The diaphragm pumps provide chemical resistance and eliminate the risk of oil contamination. Rotary vane pumps bring reliability and efficient vacuum generation, while roots pumps offer high pumping speeds. This integrated setup offers improved performance, including chemical resistance, low ultimate vacuum, high pumping speed, and reduced hydrocarbon contamination.

By implementing a combination of different pumps such as rotary vane, and/or roots pumps in series, a more efficient vacuum pumping solution can be achieved. This approach allows for a better use of the advantages of each pump type while mitigating their disadvantages, resulting in an optimized system for applications where chemical resistance, low contamination, and efficient vacuum generation are crucial.

2.4 Liquid Ring Pump

2.4.1 Mechanism

Liquid ring vacuum pump is a type of vacuum pump that is readily available in the market due to its multiple uses in a wide range of industries. For example, in the aircraft industry and automobile industry, it is usually used for vacuum filling of fluid, and in the dairy industry, it is used for the deodorization of milk under vacuum [49].

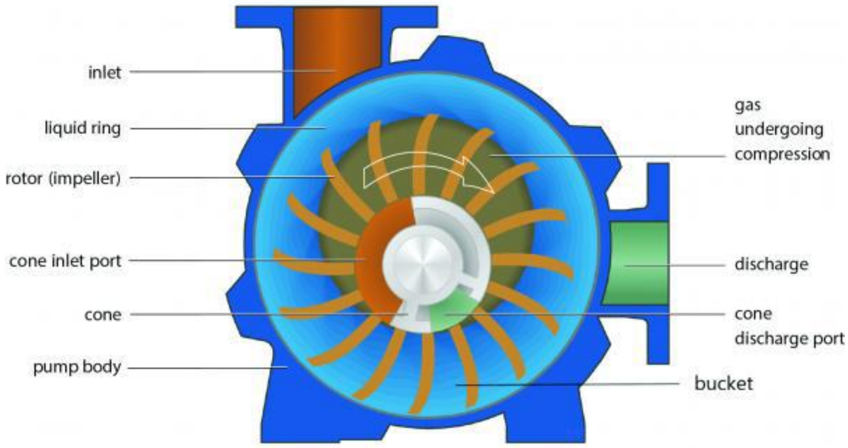

Figure 8: Sections of a liquid ring pump [7]

In Figure 8, the center of the impeller is displaced from the center of the pump. The eccentrically mounted impeller rotates in a housing partially filled with operating fluid, which is usually water. The impeller blades dip into the fluid, and the centrifugal force exerted by their rotation forms a so-called liquid ring within the housing, similar to the movement of liquid in a washing machine. This liquid ring is represented by the blue ring shown in the diagram above. The space between two blades is called a 'bucket' as the pumped medium is transported in a bucket when two blades reach the bottom of the rotation and fill the 'bucket' with the medium. As the bucket approaches the top of the rotation, due to the centrifugal motion, water moves away from the centre of the rotor, pulling from the inlet port as it does so. When the bucket returns to the bottom of the rotation and is filled with liquid again, the gas is then pushed out and expelled through the discharge port [50]. Within the pump, the liquid acts as a piston, bringing gas in and discharging it out mechanically, which is why the pump is sometimes known as a 'water piston pump'.

Since the gas is expelled through the medium, part of the operating liquid also flows out of the pump along with it and hence, the medium within the pump needs to constantly be replenished by fresh liquid [51]. This continuous flow of the operating liquid also discharges the heat formed from the gas compression within the pump, thereby cooling the pump. The liquid must not contain solid granular materials, such as sand. Otherwise, the casing will be subjected to heavy wear and may cause the pump to malfunction by jamming the impeller. There are three main methods to replenish operating liquid; a once-through system, whereby there is no recovery of the liquid, a partial recovery system, and a total recovery system [52].

In a once-through system, the process is simple as the water is continuously fed into and right back out of the pump. In a partial recovery system as shown in Figure 9, some of the fluid remains in the pump for an extended amount of time. As some of the fluid leaves the pump, the reservoir continues to feed the pump to replenish it. For this system, it is important to consider the liquid temperature of the recovered liquid, as the discharged medium will have a greater temperature, which could potentially result in cavitation of the pump and lower performance of the pump. In a full recovery or total recirculation system, the fluid is contained in a closed-loop system and is continuously recycled.

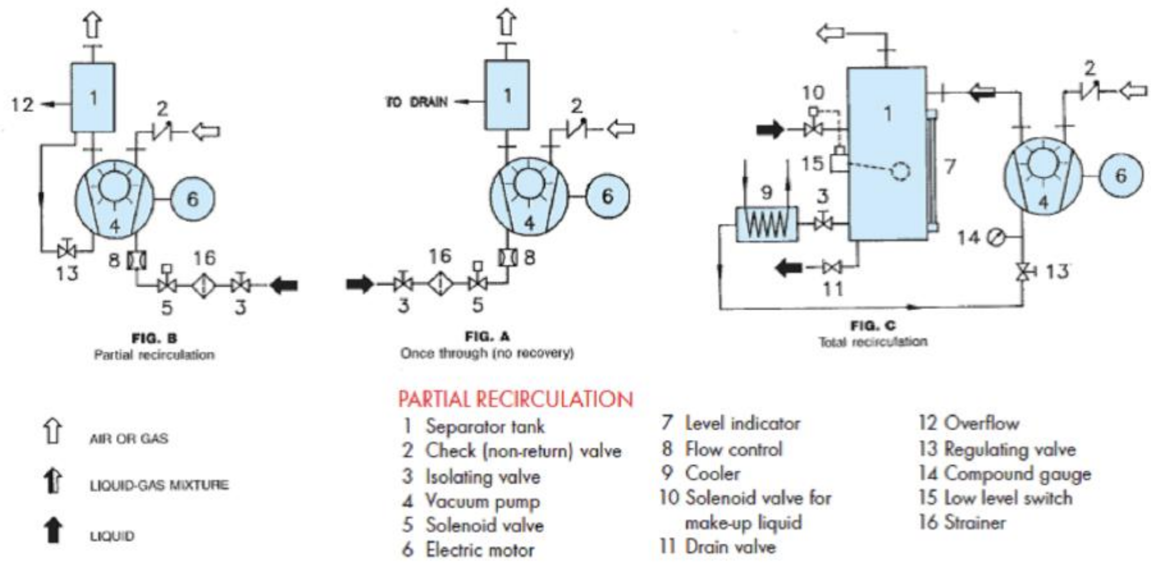

Figure 9: Partial recirculation of a liquid ring pump [8]

2.4.2 Advantages

The main advantages of liquid ring pumps are that they are easy to maintain and have the ability to handle a wide range of gases. First and foremost, the liquid ring pump does not require any lubricant for its cavity as there is no metal-to-metal contact. Even for specific pumps which are equipped with grease zerks, their bearings are only lubricated once per year or every 3000 hours, whichever comes first [53]. In addition to this, these grease-lubricated bearings are mounted externally of the chamber of the pump and hence, it does not require extra work and care when maintaining the pump. Overall, this also reduces the maintenance costs of the pump [54].

Table 2: Comparison between Liquid Ring Pump and a Dry Screw Pump [25]

Liquid Ring Pump Tolerances						
Type	Wet gas/vapor streams	Erosive gas/vapor streams	Corrosive gas/vapor streams	Reactive gas/vapor streams	Explosive gas/vapor streams	Toxic/vapor streams
Liquid Ring	High tolerance for condensing and slugs. Liquid ring efficiency increases with condensing.	Liberal internal clearances will allow up to 1/4 inch soft solids. Lobe/barrel purge will allow the ingestion of abrasive materials successfully.	A wide variety is available, including 316SS, Hastelloy, and Titanium.	Inherent cool discharge temperatures can eliminate the concern of gas/vapor reaction.	Inherent cool discharge temperatures due to nearly isothermal compression; water sealing the liquid ring can act as a flame arrestor.	Packings and a variety of mechanical seal plans are available including API 682.

When compared to other pumps, it can be noted that the liquid ring pump is able to handle a wider range of gases. This is because the gases in the pump cavity are compressed under almost the same temperature, and hence, the liquid ring vacuum pump is able to pump flammable or explosive gases. Table 2 illustrates how the liquid ring vacuum pump has a better tolerance for harsh gases and heavy vapor loads. Additionally, it is able to serve as a direct-contact condenser whereby elements within the vapor load that enters the pump, will condense inside the liquid ring and hence, improve the efficiency of the pump.

Liquid ring pumps are generally less complex to manufacture due to their wider tolerances between the blades, end plates, and the body of the pump. This feature becomes even more beneficial as the liquid ring pump has a low temperature rise as most of the heat produced from the gas compression is absorbed by the liquid seal. This is significantly important as heat production and transfer are one of the biggest challenges in developing a hyperloop system. Due to the presence of the vacuum, the heat produced from the operation of the equipment is difficult to transfer and if a proper solution is not developed, the system may overheat and face damage over time. This is less likely to happen if liquid ring pumps are used due to their low temperature rise. These characteristics of the pump allow it to be manufactured with a variety of metals, and hence, there are many alternatives to the design of the parts of the pump to increase its efficiency through its rotational speed and the position of its bearings.

2.4.3 Disadvantages

The liquid ring vacuum pump also has a few disadvantages, with the first being that liquid ring pumps require more power to form and maintain the liquid ring. As a result, these pumps are required to be equipped with suitable motors that are able to provide them more energy, approximately an additional 20-25%, than what is required by a regular pump. If a total recirculation system is implemented, the system will become more energy-intensive due to the additional equipment within the system such as motors and chillers. Additionally, it is estimated that about a third of the energy consumed by the pump is lost through the movement of the water and through internal leakage, if there is any present. Hence, even though the maintenance cost of the pump is expected to be low, the cost from the energy consumption of the pump is far greater and hence, is extremely disadvantageous.

As explained under Section 2.4.1, the liquid seal is a significant part of the mechanism of the part to achieve a vacuum and hence, requires a steady flow of water. In addition to this, a cooling water system may also be necessary to control the heat produced during the operation of the pump. Hence, when operating a liquid ring pump, there is a need for high water consumption. This is considered a major disadvantage as it is more expensive to dispose of the water used than it is to supply the water, adding to the high cost of a liquid ring pump system. In addition, depending on the type of water used for the system, there may be additional costs to treat the water first before using it to supply the pump. However, it also depends on what recovery method is implemented as discussed in the initial section.

These additional requirements for a liquid ring pump system will occupy more space within the hyperloop infrastructure. In a Hyperloop system, the interior space of the tube and the infrastructure are crucial factors to maximise to ensure the system's efficiency and passenger comfort. Including these extra system requirements may compromise these aspects while raising the construction and maintenance costs of a hyperloop system.

Finally, cavitation, which is a common phenomenon in pumps, also poses an issue. The liquid vaporisation which occurs in the chamber can lead to cavitation, resulting in a potential hydraulic impact on the equipment. When the internal pressure of the liquid drops and is lower than the saturated vapor pressure of the liquid at this temperature, bubbles or air pockets are formed in the local area [55]. When the pressure of the gases within the pump rises due to compression, the bubbles are suddenly crushed by the surrounding pressure, causing the surrounding liquid to quickly fill the original bubble cavity, resulting in hydraulic shock. This impact stress can be within the range of hundreds to thousands of atmospheric pressure. In extreme cases, the internal wall of the pump can start to corrode, and in the long run, be broken down especially if the cavitation process is continuous.

There are multiple ways to prevent cavitation from occurring in liquid ring pumps. Since liquid vaporisation is a significant factor in the phenomenon, the liquid used in the pump should not reach a boiling state or be vaporised during the operation of the pump. Hence, controlling the temperature is important, even though during the operation of the pump, the temperature is expected to always be constant. The main cause of the temperature rise of the liquid would be the heat of compression produced, which gets absorbed by the medium of the liquid seal. In addition to this, when gas enters the pumps and undergoes condensation, the heat from this process also gets absorbed into the medium. Therefore, the

Figure 10: Sections of a liquid ring pump [9]

liquid used must be kept at a low temperature to avoid vaporisation and the quantity of the liquid must be conserved to ensure that the outlet water temperature remains lower than the saturation temperature due to pressure within the pump.

An alternative option would be to use protective coatings such as polyurethane resin, which is described to be a flexible rubber material. Such characteristics of the coating are able to handle the high pressure areas where cavitation and erosion occur. Another advantage of the coating would be that it has good adhesion to the various metals and can easily be applied through injection or forming techniques. However, it should be noted the quality of these coatings will deteriorate over time and may require replacement, which only increases the overall maintenance cost of the pump.

2.5 Efficiency of Pumps

Nomenclature

η Coefficient of efficiency

n Rotational speed

p_a Atmospheric pressure

Q_{eff} Quantity of gas effectively pumped by a vacuum pump

Q_{iR} Quantity gas lost or internal leakage

Q_{min} Minimum quantity of gas required to be pumped by a vacuum pump

Q_{th} Quantity of gas theoretically pumped by a vacuum pump

S_{th} Theoretical pumping speed

t Evacuation time

V_S Volume of track tube

V_{iR} Volume of internal leakage

Quantity of gas effectively pumped by a vacuum pump, Q_{eff} is calculated from Equation 1, involving the theoretically pumped quantity of gas, Q_{th} and the quantity gas lost or internal leakage, Q_{iR} [28].

$$Q_{eff} = Q_{th} - Q_{iR} \tag{1}$$

Q_{th} is determined from Equation 2, where p_a is the intake pressure and S_{th} is the theoretical pumping speed. p_a is assumed to be at atmospheric pressure, 101325 Pa.

$$Q_{th} = p_a \cdot S_{th} \tag{2}$$

S_{th} is the product of rotational speed, n and pumping volume, V_S shown in Equation 3. V_S is essentially the track tube's volume. Assuming the cylindrical tube is at a 100m long basis with an internal diameter, dinner of 3.2m at an optimum blockage ratio of 0.7, V_S will then be calculated as expressed in Equation 4.

$$S_{th} = n \cdot V_S \tag{3}$$

$$\begin{aligned} V_s &= \pi \cdot \left(\frac{d_{inner}}{2}\right)^2 \cdot L \\ &= \pi \cdot \left(\frac{3.2m}{2}\right)^2 \cdot 100m \\ &= 804m^3 \end{aligned} \tag{4}$$

Rotational speed of a pump, n holds significant importance. It directly affects the pumping performance of a pump. The rotational speed of a pump involves a balance between factors such as pumping speed, energy consumption, pump performance, reliability, and noise generation. Increasing the rotational speed can improve pumping speed and evacuation time but may result in higher energy consumption, increased wear, maintenance needs, reduced longevity, and potentially higher noise levels. Finding the optimal rotational speed requires careful consideration of these trade-offs and the specific requirements of its application. Therefore, in this calculation example, 55 000, 20 000 and 90 000 revolutions per minute (rpm) will be used as an approximation for mean, lower and upper bounds since generally 20 000 to 90 000 rpm is applied in a hyperloop situation, where maintaining a low-pressure vacuum is required, thus making even a minor malfunction potentially lead to severe pump failure [56].

Q_{iR} is determined from Equation 5, which has a similar structure to Equation 3, whereby the speed, n is multiplied by the internal leakage volume, V_{iR}. Leybold has provided three values of leak rate going from very tight to not tight, i.e. ranging from 1×10^{-6} to $1 \times 10^{-4} mbar \cdot l/s$ [57]. Taking into account a worst case scenario, whereby all of the sealed connections are loose, V_{iR} can be assumed to be $1 \times 10^{-4} mbar \cdot l/s$ or in SI terms, $1 \times 10^{-5} Pa \cdot m^3/s$ multiplied by the evacuation time, t, which is calculated to be 8028 seconds from Section 3.6.2.

$$Q_{iR} = n \cdot V_{iR} \cdot t \tag{5}$$

Table 3: A summary of expected pumps' efficiencies at different rotational speeds n

n (rpm)	**n (1/s)**	$\mathbf{S_{th}}$ **(m³/s)**	$\mathbf{Q_{th}}$ **(W)**	$\mathbf{Q_{iR}}$ **(W)**	$\mathbf{Q_{eff}}$ **(W)**
20000	333.33	2.67×10^5	2.73×10^{10}	26.76	2.73×10^{10}
55000	916.66	7.36×10^5	7.53×10^{10}	73.59	7.53×10^{10}
90000	1500.00	1.21×10^6	1.24×10^{11}	120.42	1.24×10^{11}

By utilising these equations, the minimum quantity of gas effectively pumped by a vacuum pump in a hyperloop system can be determined and are tabulated in Table 3 for rotational speeds of 20 000, 55 000, and 90 000 rpm. To determine how efficient roots, rotary vane, and liquid ring pumps would be in a hyperloop system, a coefficient efficiency, η can be calculated from Equation 6, i.e ratio of the theoretical quantity of gas required to be pumped by the respective vacuum pump, Q_{pump} and the minimum quantity of gas required to be pumped by a vacuum pump, Q_{min}. The value of Q_{min} used for the equation below is the value Q_{eff} corresponding to 55 000 rpm as it is the mean rotational speed.

$$\eta = \left(\frac{Q_{pump}}{Q_{eff}}\right) \tag{6}$$

The value of Q_{pump} can be determined using Equation 1 and substituting the rotational speed, n as the maximum rotational speed of the vacuum pump. The values of the maximum rotational speed of each pump (roots, rotary vane, liquid ring), are tabulated in Table 4 below, which are then used to calculate the corresponding Q_{pump} and η for each pump.

Table 4: A summary of roots, rotary vane and liquid ring pumps' efficiencies at their maximum rotational speed, n [26, 27]

Vacuum pump	n (rpm)	**n (1/s)**	$\mathbf{S_{th}}$ **(m^3/s)**	$\mathbf{Q_{th}}$ **(W)**	$\mathbf{Q_{iR}}$ **(W)**	$\mathbf{Q_{pump}}$ **(W)**	η
Roots pump	3000	50.00	4.02×10^4	4.07×10^9	4.01	4.07×10^9	0.15
Rotary vane pump	1750	29.17	2.35×10^4	2.37×10^9	2.34	2.37×10^9	0.09
Liquid ring pump	1800	30.00	2.41×10^4	2.44×10^9	2.41	2.44×10^9	0.09

As observed from Table 4, the most efficient vacuum pump is deduced to be the roots pump, while the least efficient vacuum pumps are both the rotary vane and liquid ring pumps. However, it should be noted that the coefficients of efficiency for every pump in Table 4 is extremely low and hence, none of the pumps are neither sufficiently powerful nor efficient to support a hyperloop system.

2.6 Comparison of Pumps

Table 5: Comparison of Roots Pump, Rotary Vane Pump and Liquid Ring Pump

Vacuum pump	**Main advantages**	**Main disadvantages**	**Efficiency of pump, η**
Roots pump	• High pumping speed to reach medium and high vacuum levels. • Long service life without the need of maintenance. • Excellent pressure recovery capability.	• May require additional vacuum stages or support from additional pumps to achieve extremely high vacuum levels. • High energy consumption to achieve greater efficiency.	0.15
Rotary vane pump	• Able to generate medium and high vacuum levels. • Minimal maintenance requirements, hence have longer operational lifetime.	• Needs to be paired with other pumps to achieve higher vacuum levels. • Slower pump-down process if used alone in a system.	0.09
Liquid ring pump	• Produces less heat and hence, has a lower temperature rise. • Lower complexity in constructing the pump, allows for easier maintenance of pump.	• May require additional systems such as a cooling system and a constant water supply system, and hence, construction of the system may be more complicated and difficult to pair with other pumps. • Lower pumping speed, and hence may not be able to reach high vacuum levels as required.	0.09

From Table 5, it can be deduced that among the three pumps, the roots pump is the most well-suited vacuum pump for the demands of a hyperloop system. The main reasons for this choice are because it is determined to be the most efficient vacuum pump compared to the rotary vane and liquid ring pump, and is capable of achieving high vacuum levels without additional support while still requiring minimal maintenance.

However, even though it is the most efficient, its efficiency is still significantly low as shown by its efficiency coefficient, η with a value of 0.15. In addition to this, as mentioned in the table above, roots pumps will require additional support such as additional pumps to be able to achieve and maintain higher vacuum levels. Therefore, it is proposed that instead of using the roots pump as the sole type of vacuum pump in a hyperloop system, it should be paired with other pumps to be able to achieve greater efficiency. In this case, the rotary vane pump is the better option as an additional 'backing' pump as discussed in Section 3.2.2. This is mostly because rotary vane pumps are much easier to integrate into a system with other pumps as compared to liquid ring pumps, which may over complicate a system due to their requirement of a cooling and water supply system. More research and detailed calculations will be required to confirm if this combination and arrangement of vacuum pumps will be able to create an optimum hyperloop system. It should also be noted that having multiple types of pumps in a hyperloop system will also require more maintenance, which also raises the cost of the overall system. Hence, the drawbacks of implementing a multi-pump system need to also be further investigated to identify any hazardous technical complications. Another viable solution would be implementing entrapment vacuum pumps instead. While these type of pumps are more expensive, entrapment vacuum pumps are able to achieve high vacuum levels at a faster rate and may allow for a more efficient system. Further research is recommended to establish this statement and to investigate the feasibility of using these pumps for a hyperloop system, compared to utilising gas displacement pumps.

2.7 Monitoring and Maintaining Pressure at a Vacuum Level

2.7.1 Monitoring Pressure

Monitoring pressure in a hyperloop track system is of paramount importance to ensure safe and efficient operation. Implementing appropriate monitoring strategies and utilising advanced technologies can enhance system reliability and facilitate timely response to pressure variations. This section suggest methods in monitoring pressure/vacuum effectively in a hyperloop track system.

Firstly, a network of multiple low range pressure sensors should be installed strategically along the tube [58]. These sensors should be placed at regular intervals to capture accurate pressure readings throughout the system. By having multiple sensors, pressure differentials and fluctuations can be monitored comprehensively in real-time. The data from these sensors can be continuously recorded and analysed to identify trends or anomalies that may require attention or adjustments in the pumping system.

Low-pressure measuring devices generally have larger dimensions compared to equivalent higher-range devices due to the fact that lower pressures result in minimal deformation in the sensing material [59]. To maintain the desired level of sensitivity in measuring low pressures, a larger surface area is required. Although a thinner material is utilised, technological limitations and the strength of the active material often impose restrictions. As a consequence of the larger surface area and thinner sensing material employed in low-pressure sensors, accuracy performance needs to be slightly downgraded compared to higher range devices. This is because they are more susceptible to external environmental factors such as vibration and fluctuations in temperature. Besides that, a centralised monitoring system should be implemented to collect and integrate data from all the pressure sensors installed along the track. Such systems should provide real-time visualisation of pressure levels and enable operators to quickly identify and respond to any pressure variations or emergencies. The monitoring system can also be equipped with alarms or alerts to notify operators of critical pressure thresholds being reached or exceeded. Furthermore, data logging and trend analysis functionalities can be incorporated to facilitate long-term performance evaluation and predictive maintenance.

Next, enabling remote monitoring and control capabilities for pressure monitoring is vital. This allows operators and maintenance personnel to access real-time pressure data, receive alerts, and make adjustments remotely. Remote monitoring provides flexibility and facilitates timely response, even in situations where on-site access may be limited. By leveraging remote connectivity, operators can continuously monitor pressure levels and take immediate action to maintain the desired vacuum conditions, ensuring optimal system performance and passenger safety. A real-life example can be taken from the London Underground initiation in predicting and preventing track circuit failures that could lead to disruptions for the travelling public at the Victoria Line. The system deployed a central condition monitoring server that processed a live data stream from CompactRIO devices distributed across multiple sites. The server compared the received data to defined standards and made independent decisions about the health of each track circuit. Alerts were sent to a human machine interface (HMI) for faster response times and displayed on touch screen devices located in control centres and equipment rooms [60].

Moreover, an integrated system diagnostics feature should be implemented within the pressure monitoring system. This attribute should analyse the collected data, identify potential issues, and provide actionable insights to maintain optimal performance. Using advanced algorithms and machine learning techniques, the system can effectively detect abnormal pressure patterns, accurately predict maintenance requirements, and provide valuable suggestions for optimising the pumping system [61]. This proactive approach to system diagnostics can help prevent unexpected downtime, improve overall system efficiency, and extend the lifespan of the equipment.

Regular maintenance and calibration of the pressure monitoring equipment are also crucial to minimise the chance of erroneous readings [62]. A comprehensive maintenance schedule should be established, including routine inspections, cleaning, and calibration of the pressure sensors. This will help maintain the accuracy of the pressure data and ensure that the monitoring system remains in optimal working condition. Additionally, regular training and proficiency testing for operators and maintenance personnel should be conducted to ensure they have the necessary skills and knowledge to operate and maintain the pressure monitoring system effectively.

2.7.2 Maintaining Pressure

Segmenting the track tube is an imperative consideration for avoiding the need to maintain a vacuum state over hundreds of kilometres. This approach provides numerous advantages in terms of optimising maintenance processes, enhancing system dependability, and ensuring cost efficiency. Several effective strategies are listed below for adequate tube sectioning.

Primarily, maintaining the integrity of segmented tubes and preventing air seepage from failed pumps are critical concerns. Alongside the segmenting approach, incorporating an emergency shut-off valve, such as the Vacuum Pump Isolation (VPI) valve shown in Figure 11, enhances system safety and functionality. The VPI valve features a solenoid valve that operates in parallel with the electrical supply of the vacuum system [10]. When the vacuum pump is operational, the solenoid valve remains closed, ensuring the vacuum system and the VPI valve's body remain free of air. However, in the event of an electrical power interruption to the vacuum pump, the solenoid valve opens, allowing air to enter the VPI valve. This swift closure isolates the vacuum system from the failed pump, leveraging the pressure difference between the atmosphere and the vacuum system to keep the valve closed without requiring additional power. Consequently, the vacuum system is effectively isolated, and controlled air admission through small openings gradually raises the pressure to atmospheric levels. Once the vacuum pump is restarted, it resumes evacuating the vacuum system, restoring the desired vacuum state. By integrating the emergency shut-off valve mechanism, such as the VPI valve, into the segmented tube design, the Hyperloop system can promptly respond to pump failures, isolate the affected area, and maintain the desired vacuum state in the remaining segments, ensuring system integrity and passenger safety.

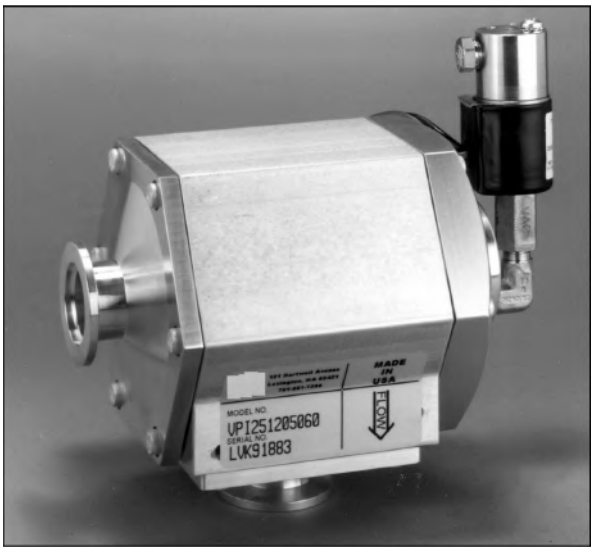

Figure 11: Vacuum Pump Isolation (VPI) Valve [10]

Another approach is the adoption of a modular tube design with a minimum of two moveable bulkheads required per tube section for the hyperloop track system. Modular tubes consist of smaller sections that can be easily connected and disconnected. The bulkheads, operating during maintenance or evacuation mode, maintain the necessary clearance and are equipped with redundant seals and pressure monitoring on both sides (vacuum and non-vacuum end) to ensure tightness between isolated and non-isolated sections. These bulkheads are retractable and are demonstrated in Figure 12. The movement of these bulkheads is powered solely by external energy, supported by fail-safe devices that securely lock them in both end positions [63]. This design also allows for flexibility in maintenance operations. If a particular section requires maintenance or repair, it can be detached from the system while other sections remain operational. This not only streamlines maintenance activities but also reduces the length of track tube that needs to maintain a vacuum state during such operations, resulting in improved efficiency and cost savings.

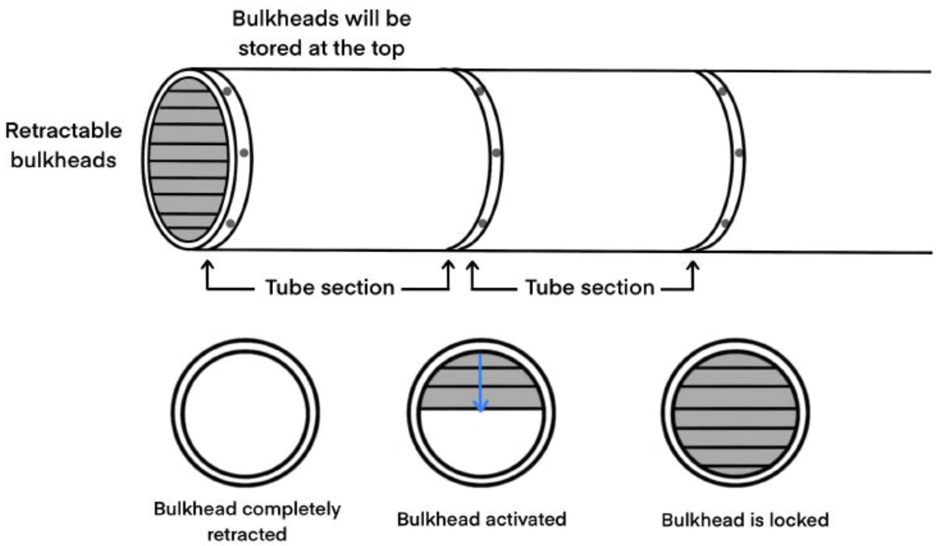

Figure 12: Diagram of retractable bulkheads for modular tube sections

Additionally, implementing comprehensive testing and monitoring systems is vital for identifying potential leaks or weaknesses in the segmented track tube. For instance, as shown in Figure 13, Hyperloop Transportation Technologies' leak detection technique involves introducing a helium composition into a vacuum-sealed track tube through the use of tube injection, vehicle injection, or a combination of both methods, thus ensuring its continuous presence [64]. These systems can include sensors, detectors, or even remote monitoring technologies. By continuously monitoring the condition of the track, any issues can be detected early on, allowing for prompt maintenance and preventing extensive vacuum loss. Regular testing and monitoring ensure that the segmented track tube remains in optimal working condition, optimising system performance and passenger safety.

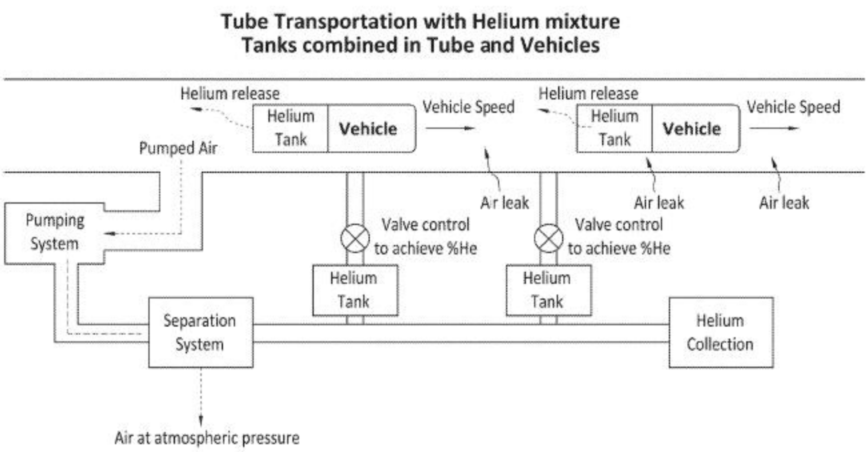

Figure 13: Hyperloop Transportation Technologies' leak detection technique

As an example, a number of roots pumps used to evacuate a certain length of vacuum track tube is estimated using the set of equations below. Roots pumps were chosen for this example as they were determined to be the most efficient vacuum pump when compared to rotary vane and liquid ring pumps in Section 3.4. Initially, a pumping speed, S has to be determined under specified operating conditions. In this case, roots pumps with an effective pumping speed at 100 Pa should be applied. This property is important as a trade-off between high and low pumping speed of a roots pump lies in the balance between faster evacuation rates and higher power consumption. A higher pumping speed allows for quicker removal of gases from the system, reducing the time required to reach the desired vacuum level. However, this typically requires a larger and more powerful pump, resulting in increased energy consumption. On the other hand, a lower pumping speed may require a longer evacuation time but can be achieved with a smaller and less energy-intensive pump.

Next, the volume of the track tube, V_S can be calculated using the formula for a cylinder expressed as Equation 7. Then, the time needed, t to evacuate this volume to the desired vacuum level can be determined by dividing the volume, V_S by the pumping speed, S and multiplying it with logarithmic of pressure ratio between the initial pressure, p_1 and target pressure, p_2 as indicated by Equation 8 [65]. Finally, the number of pumps needed, N_{pump} can be evaluated by dividing the evacuation time, t by the number of minutes per hour shown in Equation 9.

$$\begin{aligned} V_s &= \pi \cdot \left(\frac{d_{inner}}{2}\right)^2 \cdot L \\ &= \pi \cdot \left(\frac{3.2m}{2}\right)^2 \cdot 100m \\ &= 804m^3 \end{aligned} \tag{7}$$

$$\begin{aligned} t &= \left(\frac{V_s}{S}\right) \cdot \ln\left(\frac{p_1}{p_2}\right) \\ &= \left(\frac{804\, m^3}{2500\, m^3/h}\right) \cdot \ln\left(\frac{101325\, Pa}{100\, Pa}\right) \\ &= 2.23h \end{aligned} \tag{8}$$

$$\begin{aligned} N_{pump} &= t \cdot \left(\frac{1\, hour}{60\, minutes}\right) \\ &= 2.23h \cdot \left(\frac{1\, hour}{60\, minutes}\right) \\ &\approx 1: \ (2500m^3/h \text{ pumping speed) pump per 100 m length of the tube} \end{aligned} \tag{9}$$

Table 6 shows a summary of the number of roots pumps required to evacuate a 100m long with a 3.2 m internal diameter vacuum chamber. The roots pumps' pumping speeds are taken from the Leybold's catalogue [66] to demonstrate the range of roots pumps quantities needed at different pumping speeds within a 50 km long tube. It is important to note that this calculation is simplified and does not consider various factors such as system efficiency, leakage rates, or safety margins.

Table 6: A summary of roots pumps quantity needed within a 100 m long vacuum tube

S (m^3/h)	d_{inner} (m)	L (m)	V_s (m^3)	p_1 (Pa)	p_2 (Pa)	t (hour)	N_{pump}
2500	3.2	100	804	100	101345	2.23	0.0371
3000	3.2	100	804	100	101345	1.86	0.0309
4000	3.2	100	804	100	101345	1.39	0.0232
4400	3.2	100	804	100	101345	1.27	0.0211
5000	3.2	100	804	100	101345	1.11	0.0186
5280	3.2	100	804	100	101345	1.05	0.0176
7000	3.2	100	804	100	101345	0.80	0.0133
7040	3.2	100	804	100	101345	0.79	0.0132
8400	3.2	100	804	100	101345	0.66	0.0110
9800	3.2	100	804	100	101345	0.57	0.0095

In summary, the evacuation time reduces leading to a decrease in the number of roots pumps required to maintain a pressure of 100 Pa within a 100 m track tube as the pumping speed increases. Whilst it may seem beneficial to use a high pumping speed pump, they also have high energy consumption. Therefore, it is essential to consider the associated energy consumption and conduct a cost-benefit analysis before choosing the appropriate roots pump.

Ultimately, segmenting the hyperloop track tube through the use of isolation valves, modular tube designs, and testing and monitoring systems is crucial for improved reliability, and cost-effectiveness. These strategies reduce the impact of breaches or failures, enhance safety, and ensure the smooth operation of the hyperloop track system. By carefully considering and implementing these suggestions, the hyperloop infrastructure can be effectively segmented, enabling streamlined maintenance procedures and optimal performance.

2.8 Leakage Issues for Vacuum Pumps

2.8.1 Sources of Leakage

The vacuum tube in a hyperloop transport system is designed to maintain a low-pressure, high-vacuum environment to reduce air resistance and improve the system's efficiency. However, achieving and maintaining such a high vacuum level can be challenging due to various sources of leaks. In this section, the different types of leaks that can occur in the vacuum tube will be discussed along with the corresponding potential mitigations to prevent or reduce these leaks.

Before discussing leakage it is important to define "leak-tight." As engineering company Leybold says: "absolutely leak-tight components and systems do not exist." Instead, leak-tight refers to its leak rate remaining below a predetermined value for the given application, which in this case is to maintain a vacuum tube.

The types of leaks that can occur can be split into four categories. The first type of leakage that can occur is in the detachable connections of the tube, which include flanges, ground mating surfaces, and covers as shown by the example in Figure 14. Leaks in these connections can be caused by misaligned parts, damaged gaskets, or inadequate tightening torque. To prevent or reduce these leaks, proper installation techniques, high-quality gaskets, and appropriate tightening torque should be used.

Figure 14: Flange leakage [11]

The second type of leak is in permanent connections, such as solder and welding seams and glued joints as demonstrated in Figure 15. These leaks can be caused by inadequate joint preparation, insufficient heat, or improper filler materials. Mitigation for these leaks includes proper preparation of joints, using high-quality filler materials, and ensuring adequate heat input during welding or soldering.

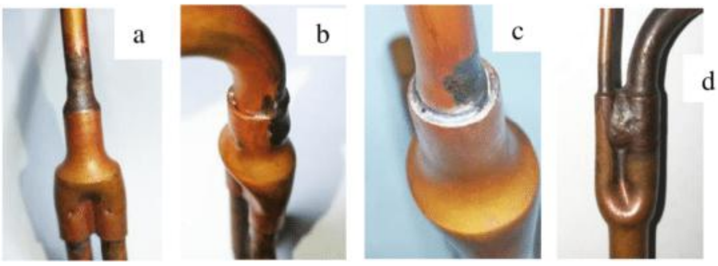

Figure 15: Solder leakage [12]

The third type of leak is due to porosity, which can occur after mechanical deformation or thermal processing. Porosity occurs when nitrogen, oxygen, and hydrogen are absorbed into the molten weld pool and subsequently trapped within the solidified weld metal. The absorption of nitrogen and oxygen in the weld pool is often a result of insufficient gas shielding during the welding process, so care should be taken to avoid this. Examples can be seen in Figures 16 and 17. To mitigate these leaks, proper material selection, surface treatment, and post-processing inspection should be considered.

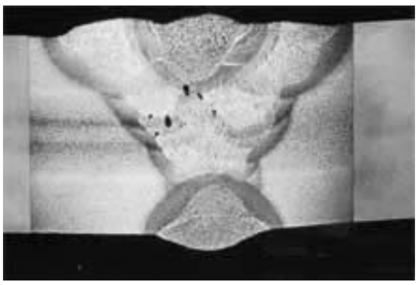

Figure 16: Uniformly distributed porosity [13]

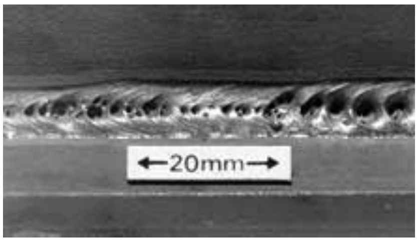

Figure 17: Surface breaking pores [13]

The fourth type of leak is thermal leaks due to extreme temperature loading, mostly at solder joints, such as the example in Figure 18. Thermal cycling can cause metal fatigue and lead to leaks. To mitigate these leaks, low-temperature solders, suitable soldering techniques, and proper heat treatment can be used.

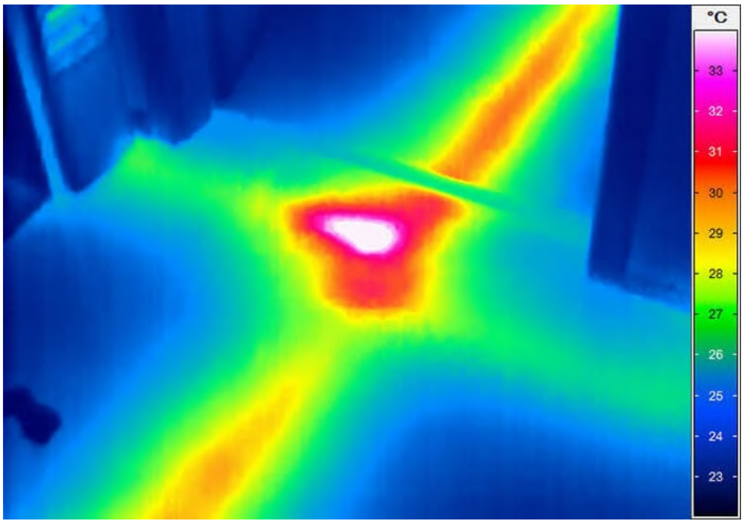

Figure 18: Thermal leakage shown with thermal imaging capture [14]

2.8.2 Mitigations for Leakage

Chan et al. discusses a "flange-type standard leak element" which serves as a calibrated leak source that emits a known and controlled flow rate of gas. This feature makes it valuable for leak detection in vacuum systems. By introducing this leak element into a vacuum system and monitoring the gas flow rate, leaks would be indicated by any deviation from the expected values of gas flow rate and pressure [67]

Additionally, the flange-type standard leak element can be utilized for leak rate measurement and system calibration. It provides a reliable and traceable standard for measuring the flow rate of gas through a leak. This information is crucial for evaluating the performance and efficiency of vacuum systems, as well as for quality control purposes.

By incorporating the flange-type standard leak element into a vacuum system, it becomes possible to establish a reference point for leak detection and control. Comparing the measured leak rates with the known flow rate from the standard leak element can help determine the severity of any leaks and enable proactive measures for repair and maintenance. Additionally, flange guards can also be utilised to efficiently seal the flanges and protect them from leakage like the examples shown in Figure 19.

Leybold utilise Helium leakage detectors which are used for the localisation of leaks, with some of their detectors also being able to determine the leakage flow rate [69]. In order for these particular detectors to work, the test part must be first evacuated, which is not ideal for the case of a hyperloop as this would cause disruptions to the transport. However, a possible solution is to perform tests at off-peak travel times. Evacuating the test part allows gas from the outside to enter through existing leaks. Helium

Figure 19: Flange guard
[68]

is introduced near the suspected leak, and it flows through the leak and is pumped out by the leak detector. The helium partial pressure within the detector is measured using a sector mass spectrometer and displayed as a leak rate, usually in terms of the volume flow of helium (pV-flow).

Helium detectors can work using three main methods; external pressure method, internal pressure method, and 'sniffer' method. These methods are illustrated in Figures 20, 21, and 22. In the external pressure method, the air within the workpiece is evacuated to create a vacuum. Helium gas is then sprayed onto the external surface of the workpiece, and the presence of helium entering the workpiece is detected using a helium leak detector.

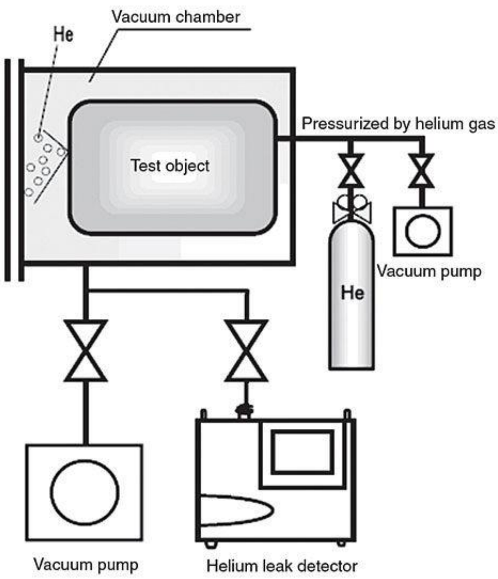

Figure 20: Spraying method or external pressure method [15]

The internal pressure method entails injecting helium gas into the workpiece within a vacuum chamber. The vacuum chamber is then evacuated to create a vacuum, and the leakage of helium from the workpiece into the vacuum chamber is detected using a helium leak detector. The "sniffer" method involves pressurizing the workpiece with helium gas and detecting the presence of helium gas from the outside of the workpiece.

Tracer gas leak testing methods are a common approach taken to detect gas leaks [70]. As above, the technique involves introducing a specific gas, known as a tracer gas, into a system or component to detect any leaks. Tracer gas leak testing offers several advantages, including high sensitivity to even

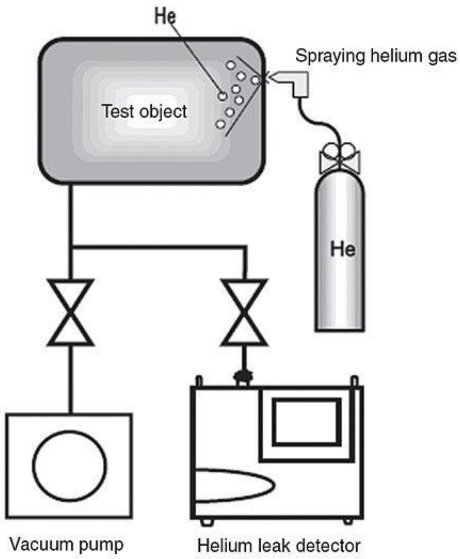

Figure 21: Overpressure and vacuum method or internal pressure method [15]

small leaks, versatility in testing various systems and components, non-destructiveness to the equipment being tested, rapid detection capabilities, accurate localization of leaks, and the common use of non-toxic and non-flammable tracer gases provides no danger of poisoning.

To detect leakages in the vacuum tube, visual inspection is important for the assessment of air leakage points in a hyperloop pod. Regularly inspecting the interior and exterior components, including seals, joints, and connections, is essential. During this inspection, careful attention should be paid to detect any visible signs indicative of air leakages, such as damage, gaps, or misalignment. This aids quick detection of any potential leakage points which will allow them to be addressed promptly, increasing both efficiency and safety. The examination of the pod's exterior involves looking at the integrity of seals located at various entry points, such as access panels, hatches, and service ports. The presence of any physical damage, such as cracks, tears, or deformities, should be carefully documented. Additionally, the examination should focus on the proper alignment of the seals with their respective mating surfaces, ensuring a secure and airtight connection.

Moving towards the interior of the pod, inspection should encompass an evaluation of joints and connections present within the pod. These include flanges, couplings, and other mechanical interfaces that may be prone to air leakage as mentioned previously. Any visible signs of wear, corrosion, or irregularities in the joint surfaces should be meticulously examined, as these can compromise the integrity of the seal and lead to air leakage.

Special attention should also be given to the examination of gaskets and O-rings, as these components play a vital role in maintaining an airtight seal. Inspecting for any signs of deterioration, compression set, or uneven wear can provide valuable insights into potential leakage points. In addition, ensuring the appropriate placement and fit of gaskets within their designated grooves or channels is crucial for preventing air leakage.

In summary, maintaining a leak-tight vacuum tube in a hyperloop system is crucial for its efficiency and safety. Different types of leaks can occur, including those in detachable and permanent connections, porosity, and thermal leaks. Proper installation techniques, high-quality materials, and adequate heat treatment are essential for mitigating these leaks. The use of calibrated leak sources and tracer gas leak testing methods is common in industry and can aid in leak detection and measurement. Regular visual inspections of the pod's interior and exterior components, such as seals, joints, and gaskets, are also necessary to identify and address potential leakage points promptly, allowing for effective repairs and maintenance. By implementing comprehensive leak prevention and detection measures, the hyperloop system can maintain the desired low-pressure, high-vacuum environment, ensuring optimal performance and reliability.

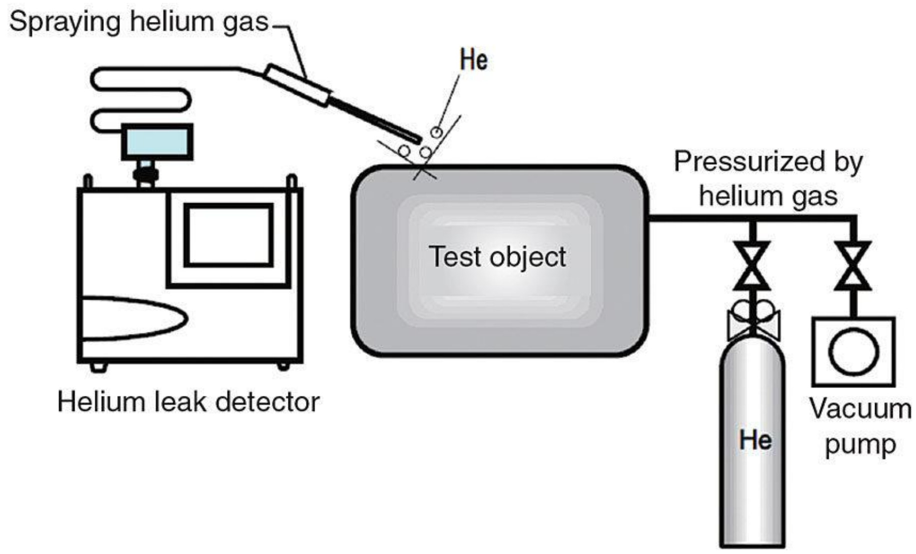

Figure 22: Sniffer method [15]

2.9 Safety Precautions for Passengers

Passenger safety is paramount in a hyperloop pod, and several precautions should be implemented to ensure their well-being throughout the journey. The structural integrity of the hyperloop pod is of utmost importance. The pod must be designed and constructed to withstand external forces and potential collisions. Regular inspections and maintenance protocols should be established to ensure the pod's structural soundness.

Secondly, emergency exits should be strategically placed and easily accessible throughout the station and tube, allowing for quick and safe evacuation in case of an emergency. These exits should be clearly marked, and passengers should be familiarised with their locations and proper usage to facilitate a swift and orderly evacuation process. Evacuation systems and procedures must adhere to several requirements. These include the feasibility of evacuation at any location along the route or at the station, considering factors like cant deficiency (lateral gravity component on tilted track) [63]. Two independent evacuation routes and procedures should be established, ensuring that the failure of one procedure does not affect the alternative. Various evacuation methods can be employed based on the situation, prioritising safety and duration. The maximum evacuation time for each procedure should not exceed 3 hours, including the time from detecting the emergency to reaching a safe environment with medical assistance. Alongside this, passengers should not remain enclosed in the capsule for more than 2 hours [63].

Effective emergency preparedness and training are crucial for ensuring passenger safety. A comprehensive emergency preparedness plan should be in place, encompassing evacuation procedures, emergency communication systems, and trained personnel who can effectively handle emergency situations. Railways and Other Guided Transport Systems (ROGS) Regulations 2006 mention that to operate as a Transport Undertaking or Infrastructure Manager, it is necessary to have a Safety Management System that complies with the regulations' requirements [71]. All staff members, including system operators and attendants, should undergo rigorous training to familiarise themselves with emergency protocols and response techniques. A similar legislation to The Fire Precautions (Sub-surface Railway Stations) (England) Regulations 2009 should also be implemented where regular drills are conducted to test the readiness of both the staff and passengers, allowing them to become familiar with emergency procedures and promoting a calm and organised response in critical situations [72].

Finally, fire safety measures must be prioritised. Although fires are prevented from occurring in the near-vacuum tubes of the track system due to the low-pressure environment, they can still pose a significant threat inside the pods themselves, where the atmosphere is not vacuum-sealed. The sealed-off nature of the pods increases the fire hazard. Fires in the pods can be initiated intentionally, such as through acts of terrorism or sabotage. Accidental fires can also happen due to numerous reasons, including issues with batteries, overheating of high-voltage components, or explosions of oxygen tanks. To mitigate the risk of fires, several safety measures can be implemented to reduce their likelihood and impact. Pods should be equipped with advanced fire detection and suppression systems to mitigate the risk of fire incidents [71]. Adequate fire exits and evacuation routes should be clearly marked and easily accessible to passengers. Regular inspections and maintenance of fire safety equipment should be conducted to ensure their functionality. Passengers should also be educated on fire safety measures and emergency response protocols to minimise panic and facilitate a safe evacuation process.

To conclude, ensuring passenger safety in a hyperloop pod requires a combination of factors, including maintaining structural integrity, implementing emergency preparedness and training programs, and prioritising fire safety measures. Through the implementation of these precautions, the hyperloop system can establish a secure and reliable transportation experience for passengers, instilling confidence in the system and promoting a safe journey for all.

3 Airlocks

The concept of airlocks is a crucial aspect in a Hyperloop system that utilises near-vacuum atmospheres to allow for high speed travel. In a Hyperloop system, pods travel at very high speed due to the minimal air resistance in the tube which is the result of the near-vacuum environment. Hence, the pressure within the tube needs to be maintained and controlled. Airlocks are described by Kassebi and Siegfried as 'devices with gate valves that allow hyperloop pods to be loaded and unloaded inside the evacuated tube without re-pressurizing the entire line, making the transition from atmospheric to low pressure and vice versa easier'. By creating a gradual change in the pressure levels, sudden and extreme differences in pressures can be avoided, and puts less stress on the overall infrastructure of the system. Hence, this reduces the risk of physical harm or discomfort of the passengers. This transitional space is usually controlled as an entry and exit point, which allows passengers or cargo to either enter or exit the pod safely and smoothly. On the other hand, repeated sudden changes in pressure could result in additional stress onto the system and increase the chances of failure due to fatigue. Furthermore, this space is separate area from the tube, making it easier to maintain the tube's infrastructure and avoid any potential damages that could deteriorate the performance of the entire system.

When designing an airlock for a hyperloop system, there are many factors to consider such as the size of the airlock, the mechanism of the sealing of the airlock and the efficiency of the airlock system in terms of allowing the passengers to board and deboard. The process includes investigating different pressure control mechanisms and sensors to establish a seamless and safe process for the passengers. The types of airlocks that will be covered in this paper are single air chamber, end door airlock, bridge doors airlock, and twin airlock chambers. The discussion of these airlocks includes how their mechanisms work, advantages and disadvantages, and potential modifications to the system. Airlocks in a hyperloop system are considered new technology and there is a significant lack of information. Therefore, the paper will not include an economic analysis of the airlocks.

3.1 Single Air Chamber

3.1.1 Mechanism

Maintaining a vacuum throughout the tube is crucial to achieving the proposed speeds and efficiencies of the hyperloop. This creates the question of maintaining this vacuum as passengers board and deboards at a hyperloop station. An airlock will seal off the different pressure zones, allowing passengers to transfer between station and pod without exposing the tube's vacuum to the outside atmosphere. One proposed airlock is a single air chamber. In this scenario, upon arrival the pod will enter the volume of the airlock, the tube-side door will then close and seal, then compressors will bring the air pressure within the airlock up to atmospheric pressure allowing for a safe deboarding of the pod through the station-side door without compromising the vacuum of the tube. Upon departure, the pod will turn around and reenter the same airlock it used for arrival, the station-side door will close and seal, and vacuum pumps will then bring the airlock pressure down to the pressure of the tube. This method is similar to what is shown in Figure 23, however, rather than the pod entering through an airlock and leaving through a separate one, the airlock will use the same airlock for both ingress and egress [21]. This provides an intrinsic advantage as it removes the requirement for the airlock to be depressurized without a pod. This significantly improves energy efficiency and depressurizing time.

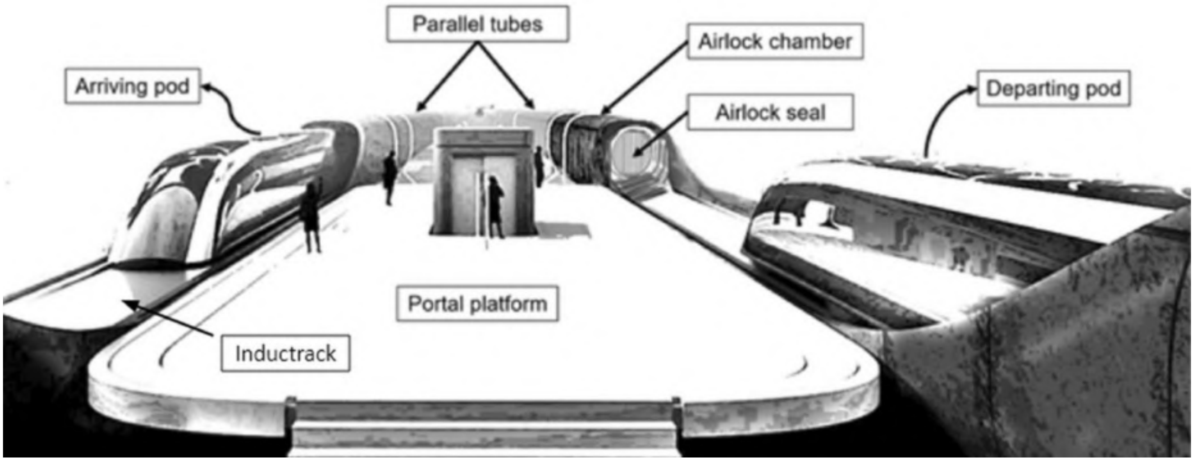

Figure 23: Schematic of the Hyperloop Portal

Still, compared to other proposed airlocks such as the airdock or end-door airlock, there is a concern over its energy efficiency and depressurizing time. One way to significantly reduce the time-energy usage is by reducing the volume surrounding the pod. Since the pod will not be entering the station at a high velocity, the Kantrowitz limit for drag plays less of a role in determining the radius of the airlock compared to the cross-sectional area of the pod. This implies that the cross-sectional area of the airlock should be reduced, compared to the tube, which will reduce the volume needed to be pumped. In the calculations shown in Section 4.1.3, it is estimated the minimum time for the pod to enter the airlock, depressurization, and pressurization without using a compressor to minimize the drag; the minimum time was found to be approximately 100 seconds. A gap of roughly 10 centimeters between the pod and the walls of the airlock will permit this sequence time. This gap provides some allowance in the event of error surrounding the pod's movement. Furthermore, keeping the compressor on the front of the pod active while the pod enters the airlock will allow for even further reductions in volume.

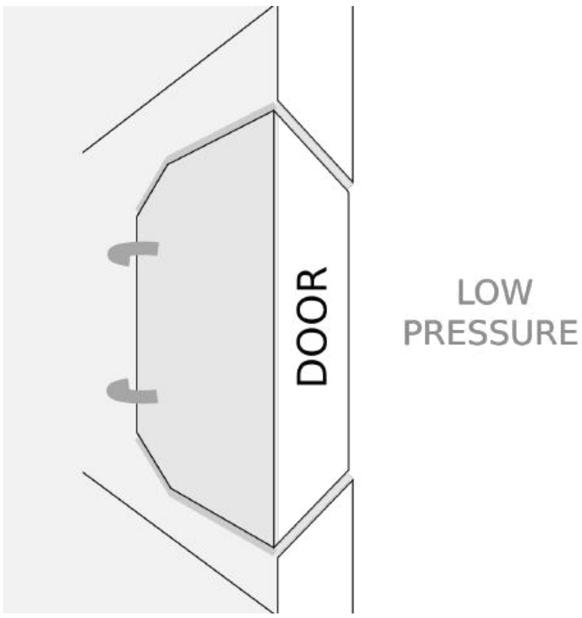

Figure 24: Plug door for a single air chamber [16]

An important aspect to consider when designing the airlock chamber is the choice of door. The first option is known as a plug door as shown by Figure 24, which utilizes the pressure differential to enact a force acting on the door in the desired direction, henceforth increasing the efficacy of the seals [73]. One advantage of plug doors is familiarity as it is the primary choice in modern vacuum transport such as airplanes or space travel [73]. Although, for a plug door to be efficient, it has to have a concave shape that is wider on the high-pressure side than the vacuum side. Due to the design reducing the area of the airlock to be smaller than the area of the tube, plug doors would be inoperative. The other option is a standard door with hermetic seals on the edges of the door. Once the pod enters the chamber, these doors would swing over the entryway before being latched by hydraulics to make sure they are sealed. Due to the relative efficiency, and operativeness of these doors, it is recommended that these are chosen for a single air chamber system.

In the feasibility study conducted by the American Institute of Aeronautics and Astronautics, the researchers found that "net energy usage is found to be relatively insensitive to pod length" [74]. This means that a full-scale implementation of a hyperloop system could have varying pod lengths and thus, these varying lengths need to be accommodated in the airlock chamber. A viable option is to have a separate airlock chamber for each length – for example, a pod of length A could go to airlock chamber I in a station while a pod of length B would go to airlock chamber II – however, this would result in several inefficiencies. For instance, if specific pod lengths are only run during certain hours, this would result in their designated airlock chambers being unutilised outside of these times. In addition, there needs to be enough airlocks to accommodate each length for every travel time, this would result in a station needing a large number of airlocks even if it only uses many of them once a day. This will increase the space required to build the station, and the complexity of the tracks that will lead the pods to their designated airlock, and thus the cost will increase as well.

The other way to accommodate varying pod lengths is to build each smaller airlock chamber inside of a larger one and so on as shown in Figure 25. This will allow for only segments of an airlock to be unutilised if specific pod lengths are not running rather than the entire chamber. For example, if a 37 m, a 32 m, and a 27 m pod were used simultaneously, all three of these pods would be able to enter the same airlock but not simultaneously. The airlock will contain pairs of chamber doors based on the length of the pod. If the 32m pod enters the airlock chamber, it will dock and then door 1 will close allowing the pod to fit while minimizing excess volume. The same applies to the 37 m pod, when it enters door 2 will close, and so on. This will greatly increase the space and cost efficiency of the airlocks should they be built to accommodate varying pod lengths.

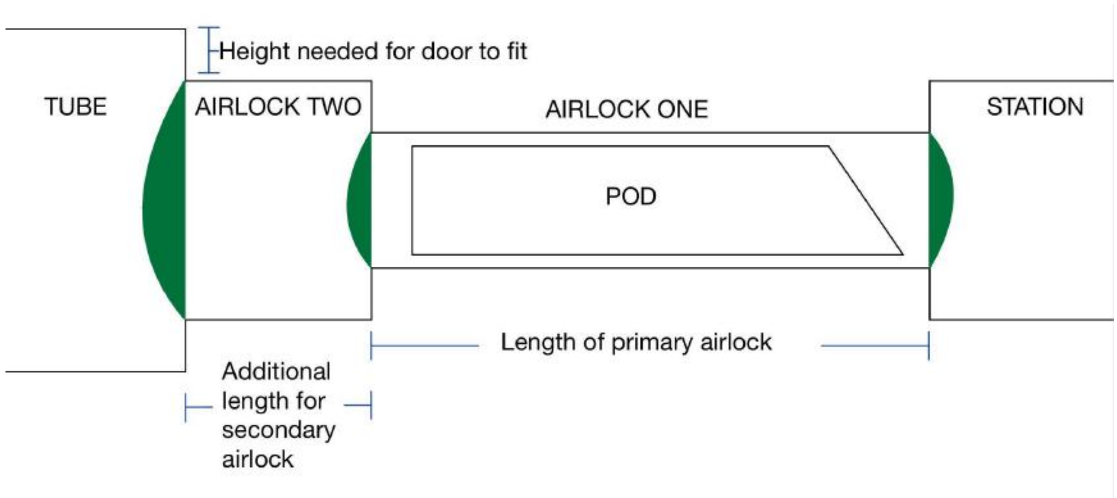

Figure 25: Diagram of airlock accommodating for varying lengths of pod.

One problem that arises with this method is that each airlock entryway would need to be wider than the latter to allow the doors to seal onto the tube material as illustrated by Figure 26. This implies that the longer pod lengths would require a disproportionate increase in pumping volume, increasing the cost and energy for the longer pod lengths. For instance, suppose that the doors must have 5 cm of overlap for any angle on the door. Now, to allow for safety the gap should be roughly 10 cm wider than the entryway/door width. Therefore, an extra 15 cm is required for the radius for a longer pod to support the door swinging and include safety precautions. This means for every extra meter of pod length, an additional 2.66 m^3 needs to be pumped out on top, discounting the increase in volume solely based on increased pod length. The efficiency of this system will largely depend on the cost of space and is thus location dependent and should be analyzed on a per-city basis.

Figure 26: CAD render of single air chamber

If the hyperloop were designed based on rail travel rather than maglev, or even just the airlock relying on a rail, a gap bridge needs to be implemented to allow the door to seal [75] as further demonstrated by Figures 27 and 28. For the pod to traverom tube to airlock and vice versa, the rail must be continuous during the transfer over the entryway of the airlock. However, to seal the airlock, the door will need to completely cover the entryway meaning that it cannot be blocked by the rail. This means that a section of the rail must be removable to allow the door to swing up and block the entryway, but must be able to return to its original position to allow the pod to travel along the rail seamlessly. ETH Zurich mechanical engineering student Nico Ege showed in his Vacuum Transport Seminar presentation showed that this is mechanically possible and thus will need to be implemented in every airlock station that relies on railways rather than maglev.

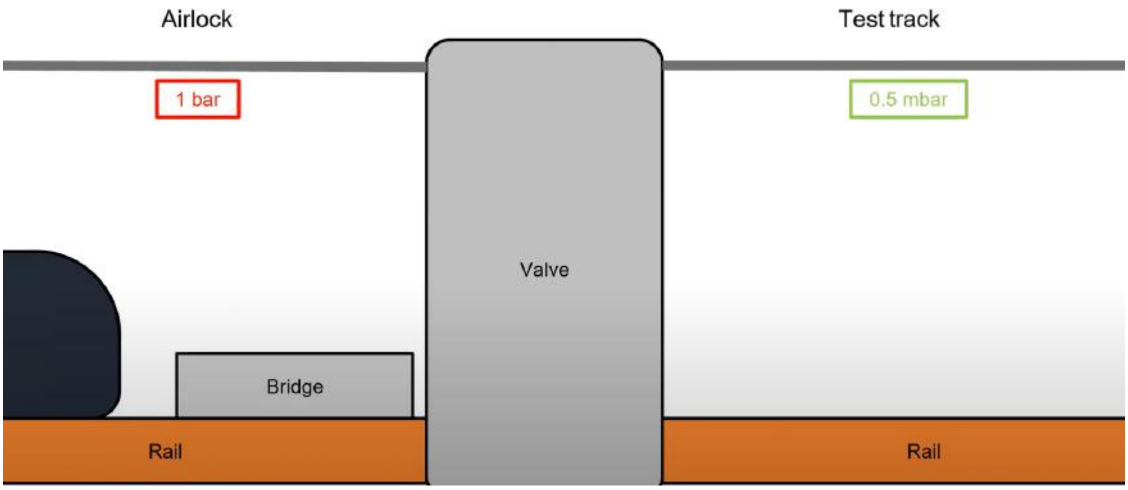

Figure 27: Door blocking preventing further movement of pod

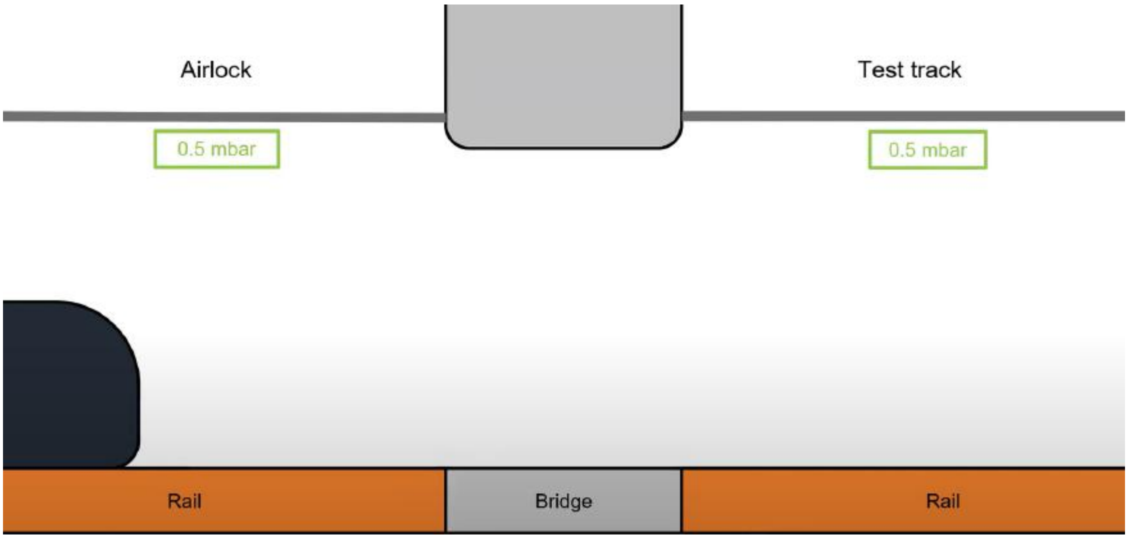

Figure 28: Door lifted for entry of pod

Due to the necessity of implementing a compressor on the front of the pod to overcome the Kantrowitz limit, it is necessary to provide a pathway for the pod to turn around in the station for the compressor to be in the direction of travel [76]. The two proposed methods for this include a turntable and a large circular track. The circular track involves the pod following a rail or tube that would take in a circular and return to the station with the pod facing in the opposite direction. One significant disadvantage to this proposal is the significant area it would require. Using the proposed pod length of twenty-seven meters and estimating the maximum pod turning angle to be ten degrees, the radius of this circular track is determined to be approximately 150 meters. This would require almost a kilometer of track to be built to turn the pod around. As many of the stations will be in large urban areas, this scale of infrastructure would require significant expenditure and raise concerns over the environmental impact.

The second proposed method for turning around the pod would be a turntable as illustrated in Figure 29. This method involves the entirety of the pod docking onto a circular turntable, which would then rotate 180 degrees, allowing the pod to exit through the way it came in. Since the area of the turntable needs to fully fit the pod, the diameter of the turntable is estimated to be 28 m. This will allow the pod's entire length to fit across the turntable while allowing room on either side. This provides a significant advantage against the circular track as it reduces the necessary infrastructure to be installed; providing an opportunity for the cost of the station to decrease significantly. However, the mechanism involved needs to be able to rotate the pod's weight, thus it will require complex engineering which will increase the cost. Further work needs to be done on analyzing the mechanics and cost of a circular turntable.

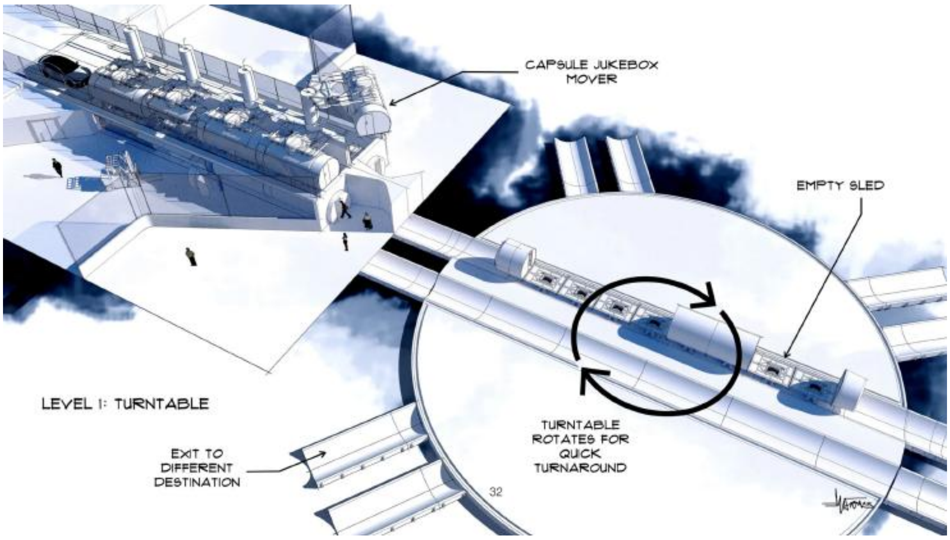

Figure 29: Argo's design for a turntable for a hyperloop pod

3.1.2 Advantages and Disadvantages

As aforementioned, the single air chamber contains several crucial advantages and disadvantages over the other airlock concepts. First of all, the same airlock is used for incoming and outgoing pods, this means that, aside from maintenance, there is no need to depressurize an airlock without a pod inside of it. This significantly reduces the necessary pumping volume when compared to the twin airlock chamber as a large majority of airlock volume will now be occupied by the pod, reducing the amount of air volume.

Secondly, while the single-air chamber is still a complex system due to the extreme conditions of the project, it is much less complex than the airdock and end-door airlock designs. For example, both the airdock and end-door airlock require a very precise mechanism that will allow the sealant doors to perfectly align with the pod or the wall while a single air chamber will only need to be within the airlock and not connected to the doors. In addition, more maintenance will need to be conducted on the airdock and end-door airlock as their actions are frequently used despite the necessity of having them be lighter and more mobile than the sealant doors used on the single air chamber. The high usage of the doors in the other systems, combined with the less durability means that they will experience more wear and tear than the single air chamber, thus raising the cost of the system and increasing the probability of an accident.

Furthermore, the relative simplicity of the design will increase the perceived safety of the single air chamber. As the system is relatively simple, the majority of people will be able to understand the basic mechanism that occurs. As discussed in Dubé et. al's paper, a lack of knowledge on a subject will make people less hesitant to use the product [77]. For example, if the encompassing mechanism of how the airlock works were complex, a greater portion of people would lose their trust in the system and thus a hyperloop would have a harder time becoming economically viable at first. Therefore, it would be in the best interest of designers to keep the basic design of the airlock as simple as possible. In addition, Kang and Kim's paper discussed the usage of social media to increase the perceived safety of a hyperloop based on the trust transfer theory [78]. This idea promotes the perceived safety of the airlock as well; by increasing the amount of media surrounding the airlock, more people will understand how it works and thus will be more likely to use a hyperloop.

One disadvantage of the single-air chamber is the necessity for the pod to be rotated before traveling back through the airlock. However, due to the necessity of a compressor in front of the pod, this is not an exclusive disadvantage [76]. While the rotating of the pod will need to be implemented into the boarding process for a station containing a single air chamber, the pod must be rotated in all the other systems as discussed. This is only true if the pod is not bilaterally symmetric and utilizes a compressor on one end of the pod only. However, should there be a compressor on either side of the pod, this would eliminate the necessity of the pod turning around before going back through the single air chamber. This scenario would provide another advantage over the twin air chamber as that system would require the pod to make some type of directional change to go through the outgoing chamber. Possibly the most significant disadvantage that arises with a single air chamber, is the necessity for an incoming pod to wait for the previous pod to complete its entire station cycle before the incoming pod can enter the airlock [79]. This is because if an incoming pod enters the airlock while the other pod is in the station, the airlock needs to be depressurized without a pod in it, drastically decreasing the efficiency of the system. This situation can be mitigated through the usage of several airlocks within a station, similar to how a station has several tracks. This would require the use of a track-switching system within the station to allow the pods to travel to designated airlocks; however, as low speeds are used within the station, this technology has already been proven and thus will be feasible.

3.1.3 System Efficiency

Due to the ever-present issue of keeping the surface area to tube width ratio below the Kantrowitz limit, there needs to be a sufficient width on either side of the pod even within the airlock. However, due to the speed being much lower within the airlock, the radius of the airlock pod can be significantly reduced compared to the rest of the tube. The Kantrowitz limit can be calculated using Equation 10, whereby v is the speed of the pod and α denotes the specific heat ratio of the air in the airlock.

$$K_{limit} = 1 - v\left(\frac{1+\frac{\alpha-1}{2}}{1+\frac{\alpha-1}{2}v^2}\right)^{\frac{\alpha+1}{2(\alpha-1)}} \tag{10}$$

By approximating the volume of the pod to be roughly similar to a cylinder, whereby the diameter of the cylinder is assumed to be 2.7 m, a minimum time for a pod to go through a single air chamber and the station can be approximated. Through formulating the total time taken, it is determined that the minimal time occurs when the pod enters the airlock at roughly 0.05 km/h, corresponding to a gap of 0.3 cm on either side of the pod. However, this minimum radius to stay within the Kantrowitz limit is smaller than the recommended gap for safety considerations.

$$t_{down} = \left(\frac{V}{v_{pump}}\right) \cdot ln\left(\frac{P_1}{P_2}\right) \tag{11}$$

$$t_{up} = \frac{V \cdot (P_1 - P_2)}{CR} \tag{12}$$

$$t_{entry} = \frac{\sqrt{2al}}{a} \tag{13}$$

Assuming the air chamber radius to have a 10 cm gap on any side results in a volume of 1.87 m^3 needing to be pumped for a 22 m pod. By assuming an effective pump down speed of 200 l/s and 40 l/s pump up speed, the pumping time of roughly calculated to be 100 seconds using Equation 11 and 12. In addition to this, due to the necessary weight of the doors to maintain the seal under high-pressure loads, 20 seconds is added to the total time to open and close the doors. In addition, it is estimated that it will take roughly 1 minute to turn the pod around. Therefore, the total time taken for a pod to go through a single air chamber will be roughly 3 minutes. Based on the 3-minute requirement for a pod to be in a station due to blocking times, a single air chamber will not cause any wasted time as it would be unsafe for pods to be leaving the station at a rate faster than once every 3 minutes [80]. Additionally, if the station is split up to accommodate several pod boardings, this will allow the incorporation of proposed safety talks, such as those given on airplanes, without reducing the time efficiency of the hyperloop [80]. Thus, it is proven that a single air chamber will be able to accommodate the proposed travel rate within safety guidelines.

3.1.4 Potential Modifications

Compared to the proposed single-air chambers, several important modifications are introduced. In summary, it is recommended that several design features should be implemented to reduce the volume of air that needs to be evacuated. This can be done through several methods: reducing the diameter of the air chamber compared to the tube, angling the doors of the chamber to better fit the geometry of the pod, and minimizing the volume of air on either end of the pod. In addition, if further research and technological development deem a safety gap of 10cm to be too large, this can further be reduced [76]. In addition, since compressors are already active in the system, keeping them active while entering the chamber can allow for a reduction in volume.

As proposed in NASA's preliminary study on the hyperloop, the energy of the pod is relatively impactful on the energy usage of the system [74]. It is proposed that a single air chamber can be divided into several air chambers of varying lengths. This will greatly reduce the necessary area needed for a hyperloop station. However, because the airlock door needs an area surrounding the entry to latch, each increasing chamber length will need to have an increased radius, thus increasing the time to deboard the pod and decreasing the time efficiency. The cost-benefit analysis will highly depend on the cost of construction in a city as well as the predicted traffic for a given station; thus this implementation should be on a per-city basis.

The last major modification proposed is splitting up the station itself to accommodate several pod airlocks at a given time. This will allow the accommodation of necessary safety implementations, such as pre-trip speeches, while still maintaining the maximum pod frequency determined by blocking time [80] [79]. It is worth noting that due to the restriction from blocking time, the frequency of once every thirty seconds proposed in the hyperloop alpha paper is not feasible on a single tube and will need several tubes running the same routes [75].

3.2 End-Door Airlock

3.2.1 Mechanism

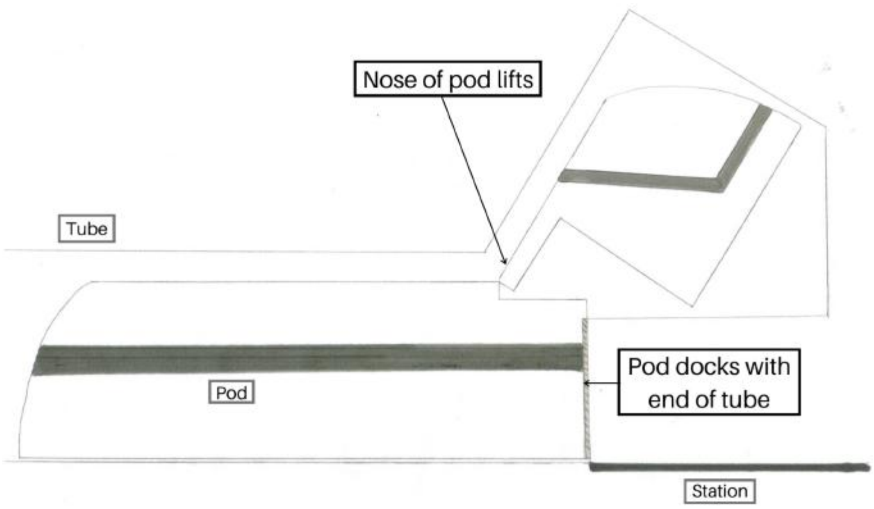

Figure 30: End door schematic [17]

Figure 30 illustrates how the end-door airlock system operates to allow the entry and exit of passengers. The premise of an end-door system draws vastly from trying to reduce the volume of the tube that requires pressurisation and it is in this spirit that it draws heavily from the aerospace sector. The main inspiration for this design comes from the NASA APAS and Quest Joint Airlock system used to connect the space shuttle to the ISS . The pod itself will be the same as aforementioned in this report (body and two aerodynamic cones). The operation of this system begins with the aerodynamic cone swinging open when the pod arrives at the station [81]. This will be covered in more detail in Section 4.2.2 as it presents a large engineering problem. The soft capture system will extend to soften the impact, to which it will then attach itself to the station mating adapter. The pod will then slowly move into the connected station and hard capture system. Once it fully moves in, there are locking pins, which rotate to create a tight seal as labelled in Figure32. After the seal has been established, the empty space is repressurised before allowing the entrance of the pod to open to allow passengers to enter or exit. Figure 31 shows a render of how the capture system is attached to the pod.

Figure 31: CAD render of pod and the capture system of an end-door airlock

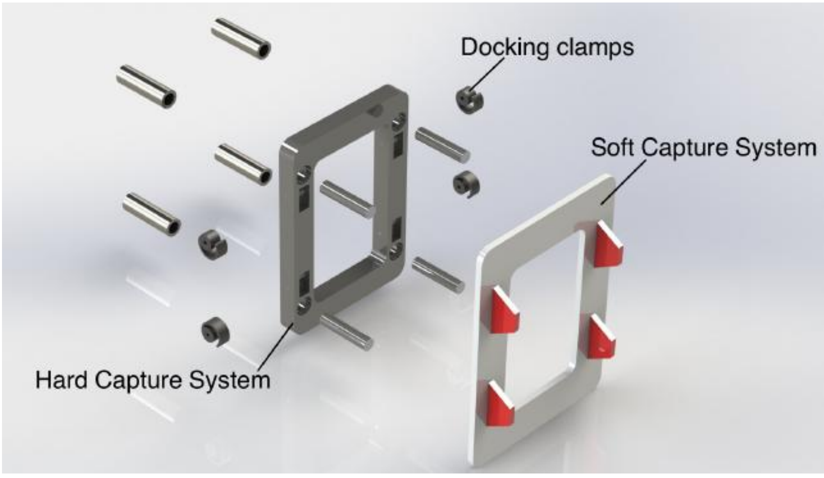

Figure 32: CAD render of the explosive view of the capture system of an end-door airlock

The sizes of the doors have been calculated to comply with the FAA minimum size for aircraft door sizes based on the number of passengers. The type chosen was Type C as it makes the best use of the possible space whilst complying with standards. The importance of optimising the given space is in order to maximise both passenger comfort and ease of access to enable efficient boarding and alighting.

3.2.2 Advantages and Disadvantages

The end-door system is most advantageous for its efficiency and its increased ease of alighting. The volume of the passenger boarding bridge is significantly reduced when compared to other designs. As there is a definitive bridge formed between the pod and the station there is no need to repressurise a significant portion of the tube in order to board and alight passengers. The hard capture system utilises a hermetically sealed 'sleeve' that will protect the passengers from the vacuum allowing for safe and efficient transit between pod and station.

With very similar technology in use with the space shuttle program, the technology has already undergone very scrutinous reviews both of safety and operational capacity. The verification of the Pressurised

Mating Adapter on the ISS showed that it is achievable to construct it in order to cope with an internal pressure of 16 PSIA (Pounds per Square Inch Absolute) this pressure is higher than what is experienced at Sea level here on earth, which is on average 14.7 PSI, showing that the structure is capable of supporting the pressure required for passengers to comfortably move between parts.

Developing on the earlier point on volume, there exists a much simpler system of parts when the End-Door system is used, as opposed to other methods listed in this paper there is no need to seal off part of the tube, which would require the use of much more complex moving parts with intricate designs. However, with such complex designs, there would also be the need for multiple high-power vacuum pumps in order to restore vacuums.

One of the biggest issues with this particular design is the fact that the aerodynamic cones are required to obey the Krankowitz Limit. These cones however result in a sloping end to the pod, whereas a flat surface is required to be able to connect flush to the station wall. In order to overcome this difficulty a system similar to that in use by Airbus on their Beluga Aircraft where the nose cone on the aircraft tilts up as shown in Figure 33. This would require extra space in the tube to allow for the opening of the pod at the end of the stations. However, there are still a few disadvantages with this design.

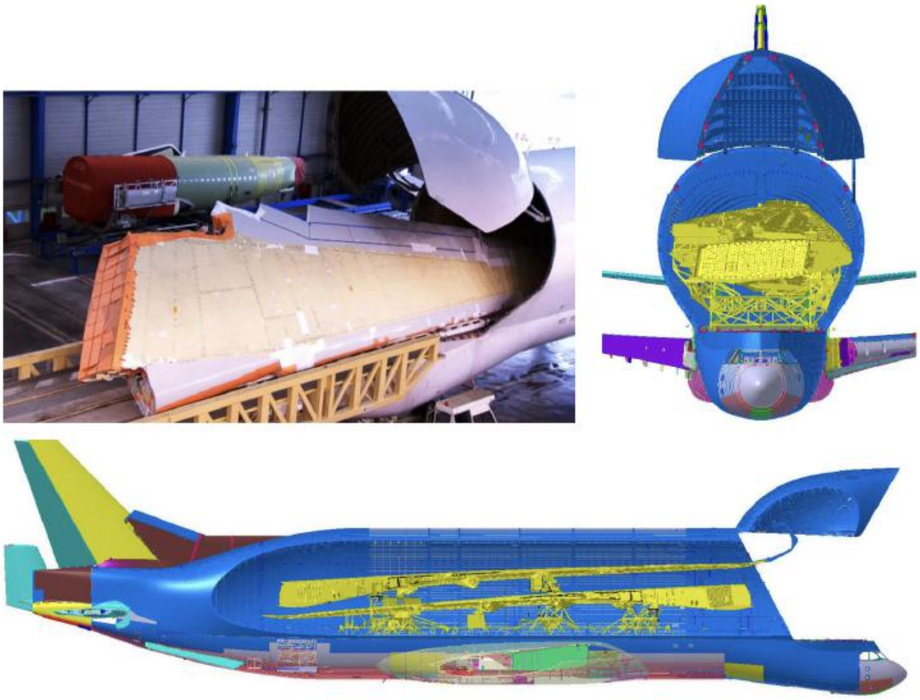

Figure 33: BelugaXL Aircraft System [18]

Moreover, one of the largest drawbacks of the end-door design is the fact there is only one door, at the end of the pod. This type of door means there is only one entry and exit point, which may lead to complications during emergency procedures. This also means that the it may take longer for passengers to enter and exit the pod. A minor disadvantage regarding the public view on the safety of this design, is that passengers may be uncomfortable or uncertain with the safety of the system due to not being able to see the pod [17].

3.2.3 Potential Modifications

A main issue that can be foreseen with this design is its conflict with accessibility and equal access laws. The United Kingdom's Inclusive Transport Policy means that public transport should be designed and operated in such a way that makes it available for as many people as possible from all backgrounds to utilise. With the narrow doorways and sleek design of the current hyperloop pods, the two seem incompatible, particularly for users who may require wheelchairs or the use of support dogs or canes. However, with further development and keen forward thinking it seems these problems can be overcome, just as they have been overcome for the likes of trains and buses.

As previously mentioned in Section 4.2.2, the single door at the end of the pod can be disadvantageous. In the future, the conceptual design of the airlock should look towards a combination of entrances and exits from the pod utilising potential bridge doors. Bridge doors airlocks are very similar to end doors in the fact that they utilise a very low volume of space to decompress, which will be discussed in Section 4.3.

3.3 Bridge Doors Airlocks

3.3.1 Mechanism

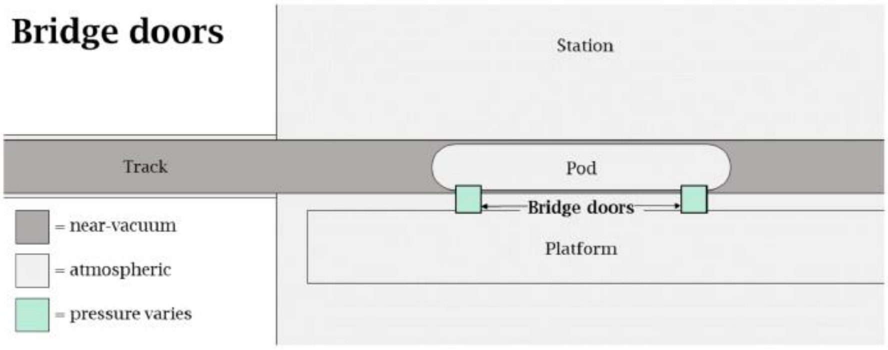

Figure 34: Simplified top-view of the bridge doors at the station. [19]

For this design, the pod remains in the vacuum environment while passengers use a pressurised and depressurised bridge to access it as illustrated by Figure 34. Similar to the end doors airlock, hooks and seals create an airtight connection, and when the bridge reaches atmospheric pressure, the doors open for entry and exit. For better visualisation, the CAD render in Figure 35 has been produced on how the bridge is attached to the pod. The first stage is the soft capture system (SCS), which establishes the initial capture of the docking vehicles. During this stage, the active docking mechanism's SCS extends, aligns with, and latches to the passive docking mechanism. Then, it stabilises the newly joined pod relative to each other. The second stage of docking is initiated after the SCS phase and is performed by the hard capture system (HCS). The HCS performs structural latching and sealing at the docking interface to transfer structural loads between the pods and create a transfer tunnel that can be pressurised for crew and cargo transfer during joint operations.

Figure 35: CAD render of bridge doors airlock capture system attached to a pod

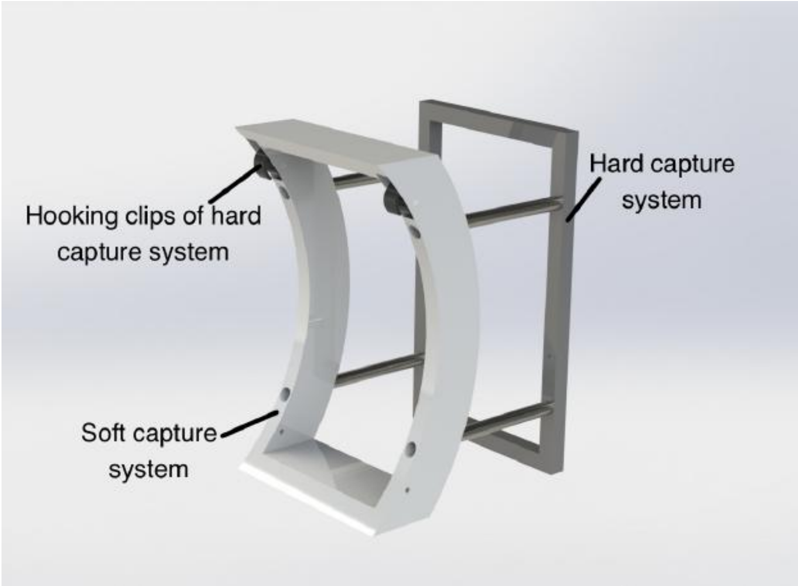

Figure 36: Labelled CAD render of bridge doors airlock capture system

3.3.2 Advantages and Disadvantages

The bridge doors system is a more efficient option for a hyperloop passenger station compared to airlock chambers. The bridge door system is also more time-efficient, with an estimated operation time of 15 seconds, as opposed to the 41.5 seconds required for the airlock chamber system [19]. This increased efficiency can be attributed to the small volume required to be depressurised (pump down time) and the ability of the bridge door system to use the same pumps for many of the bridges. This makes it the most suitable and efficient option in terms of time and requires less additional infrastructure, which results in more station space. However, its greater complexity in its design translates to a higher investment cost estimated at up to £11.8 million, in contrast to the airlock chambers which require an investment of £3.36 million [19]. This includes the need for additional pressurising tubes installed at the station, linking each door to the central pumping room, emergency pumps, and HCS and SCS, however, the lower travel time savings compensate for this. Compared to other airlocks, bridge doors would require fewer backup pumps. However, the risk of pump failure is greater due to the increased number of connections they have (as they are connected to multiple bridge doors). Therefore, the safety tube must contain backup bridge doors in case of pump failure, which will require an additional stopping position and platform. Another solution to this problem would be to utilise the time efficiency of the bridge door system during normal operation, whilst using airlock chambers as an emergency airlock due to its greater resilience in case of emergency, scheduled maintenance, or other disruptions.

However, there are still some potential drawbacks to this modification. Some passengers may experience a lower perceived safety since they will not be able to see the pod during boarding and alighting. No research has been looked into the extent this could impact the public's opinion however this could complicate and affect its adoption by the general public. Due to the high number of bridge doors in a station, compared to airlock chambers, the total bridge door system will require more monitoring and maintenance due to a large number of bridge doors. However, this will result in a mild increase in cost and should not be of much concern. Lastly, the structure of the pod will need to be reinforced around the doors to withstand the stresses and forces generated by the hooks and the HCS and SCS locking onto the pod. This will increase the weight and complexity of the pods, which could impact their overall efficiency. Moreover, this will require a redesign of the current hyperloop pod and require the bridge door airlock design to be standardised and adopted in each hyperloop station, or else these pods will only be compatible in certain lines.

3.3.3 Potential Modifications

A very crucial aspect of this design would be the positioning of the bridge. The job of the positioning system is to track the position of the bridges relative to their corresponding doors inside the tube. The system also operates the movement of the bridges to ensure that they will properly attach to the respective doors. This system is crucial to the operation of the hyperloop as it provides the means for the pod to connect with the tube to allow the process of boarding and deboarding of passengers to be more efficient. Three possible implementations of this system are discussed as follows with their respective advantages and disadvantages. These implementations are categorised as global positioning, camera tracking, and camera and laser tracking.

The global positioning system provides the global position of the pod inside the tube. Given that this is known, then, combining it with the location of the bridges, which is detected using sensors, the relative position of each bridge to the door can be determined and used to calculate a trajectory that the bridges require to take in order to reach the doors. It should be noted that this global positioning system provides both the location of the pod inside the tube, as well as the location of the doors along the tube, assuming it is already known to the system.

The main advantage of this implementation would be the simplicity of it. Assuming the location of the pod can be tracked already (e.g. to avoid collision with another pod) using sensors, this method requires no further infrastructure. However, this would mean that the system heavily depends on the sensors, which could be an issue if the global position sensor malfunctions. In that scenario, the calculated trajectories would be wrong, and the bridges will not connect with the doors. That could be potentially dangerous. Despite the known positions of the bridges through their sensors, errors are still possible, resulting in drifts, as well as noisy readings. These could be caused by vibrations. Therefore, depending on the setup, it is possible that the bridges can fail to reach the precise location of the door to attach to it.

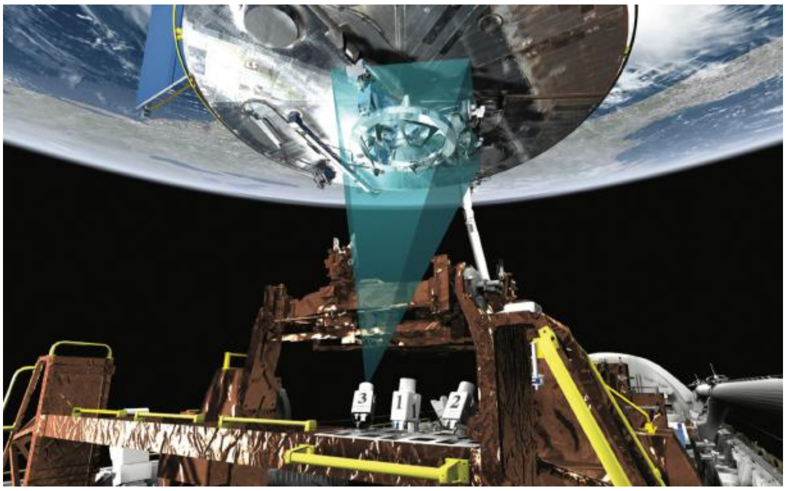

Figure 37: One of the RNS system's cameras collecting data during the Hubble's deployment back into space after the mission is complete. [20]

Camera tracking requires no knowledge of the global position of the pod and has been utilised before in other industries as shown in Figure 37. Cameras are used to track some markers. These markers could be specific signs or some coloured symbols. The idea is to achieve triangulation – using multiple points, the location of the camera can be calculated with respect to the markers and then, utilised to calculate a trajectory to reach the door. The system could be designed using a single camera to achieve monocular vision. If the angle of the camera can be computed through the provided markers, in which case the markers might require a specific shape. In this case, the system would aim to align the bridge with the door axis and then drive the bridge forward toward the door until it attaches. A depth perception, mainly the distance between the marker and the camera, can be estimated by knowing the size of the markers. This entire process is summarised in Figure 38. Another possibility is to use two cameras and achieve stereo vision. This allows for a better depth perception and hence, improves the accuracy of the system. It should be noted that this method would run in a loop. That is, all of these calculations would be performed continuously which would help with potential drift as the position, and the trajectory respectively, can be recalculated iteratively.

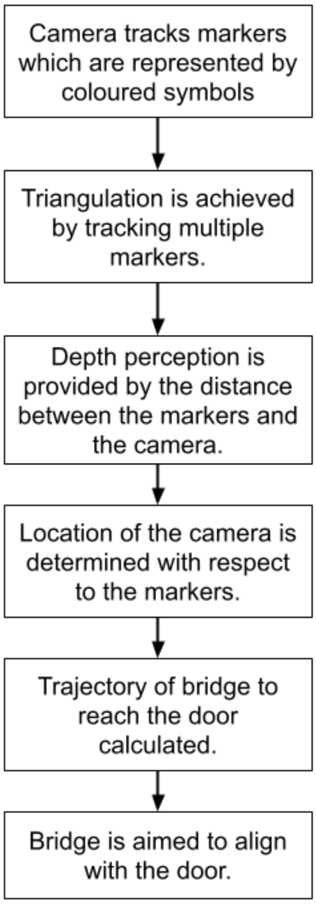

Figure 38: Diagram of process of camera tracking.

This system is beneficial since it runs locally for each bridge door. That means if one were to fail due to problems with sensors or cameras, the other bridges can still operate allowing passengers to move in and out, also improving safety. However, the markers must be clearly visible – if something obstructs them then the system might fail to calculate the location of the door which would result in the bridge not being able to attach to the door. Accumulative errors due to the cameras are still possible too. These errors are caused by the images being a discrete representation of the real world. Small errors in the calculations could accumulate over time, which is usually the case with such systems. However, this issue could be potentially mitigated as the environment is somewhat known and that knowledge could be used to correct the errors.

Similar to the camera tracking method, camera and laser tracking is also a local method and it requires a camera and a laser sensor. The idea is to use the camera to drive the laser toward a small, highly reflective spot. This could be achieved by slowly moving the sensor and iteratively calculating the direction of the movement until the sensor dot falls on the reflective spot [82]. When that occurs, the camera will be able to see the reflectance and then send a signal to the system which uses the laser sensor to calculate the distance to the spot – done via calculation of the angle of reflection. The module would know the orientation of the laser with respect to the bridge door so the trajectory can be calculated. All of that is done in a loop to allow the iterative calculation of the trajectory, helping reduce any accumulative error. Such a system would potentially require 2-3 such modules to be able to calculate the proper orientation too.

For this method, the laser could potentially improve the accuracy over the camera-only method. This also allows for a faster process to compute the trajectory of the bridge once the lasers have initially been placed on the target. On the other hand, this extension of the camera tracking method is more expensive and is more difficult to maintain due to more complex technology. Whichever method is implemented, the fact that the bridge doors are separate must be taken advantage of so they can operate as separate entities to an extent. The local methods would allow each bridge to find the closest door and to attach to it irrespective of the other bridges. This potentially improves safety over any other design as passengers can use the other bridges if one fails.

3.4 Twin Airlock Chambers

3.4.1 Mechanism

In this section, the design for the proposed twin airlock system will be explained. This system was demonstrated in the figure from the Hirde, et. al paper as shown in Figure 39. It involves two separate airlocks: (1) that used for the pod entering the station and (2) a separate system for the pod exiting. Upon arrival through the first direction of the tube, the pod will fully enter the volume of the first airlock. The tube-side door of the airlock will then close, with hermetic seals limiting any leakage of air pressure into the tube itself. An air compressor will then be applied to bring the air within the tube up to standard air pressure. The station-side door will then open, allowing the pod to enter the station and allow for its passengers to exit. The station-side door will then close and a vacuum pump will need to be engaged in order to bring the chamber down to the air pressure of the tube. While this is occurring, the pod will need to change its passengers and, if this is the final destination for the pod, turn around through an extra track or a turntable, similar to those discussed in Section 4.1.1. The process will then be mirrored for the departing pod; the station-side door of the departing air chamber will open, the pod will fully enter, and vacuum pumps will depressurise the air inside, allowing the pod to leave. The departing air chamber will need to be pressurized while it is empty as well in order for the next departing pod to be able to enter.

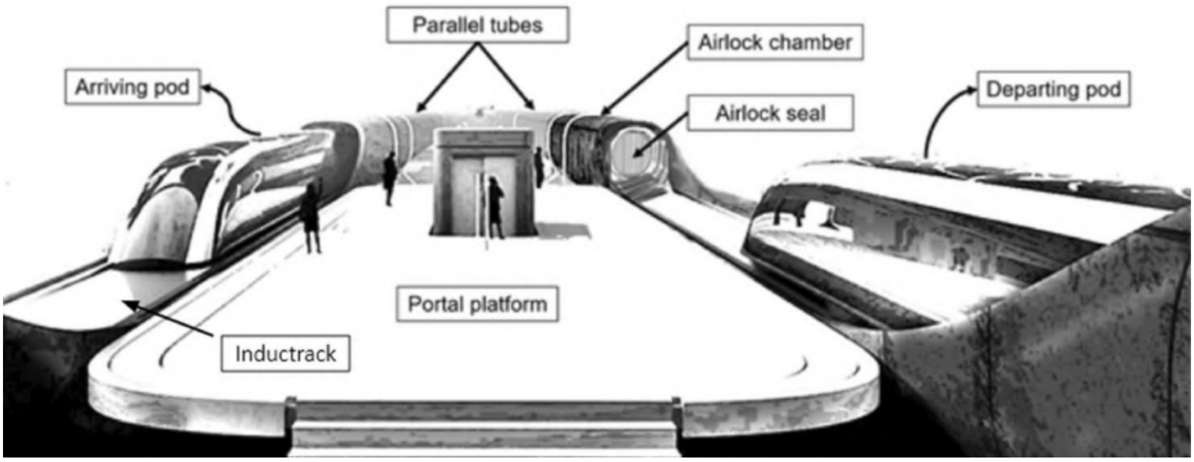

Figure 39: Twin airlock system [21]

As the twin airlock system is very similar to a single air chamber system, many of the design features are the same. For example, hermetic seal doors will be chosen over plug doors as it is required to minimize the area of the chamber and can shrink the radius relative to the tube, ruling out the usage of plug doors, which were discussed in Section 4.1.1. The term 'hermetic' is defined to be airtight and hence, a hermetic seal door is a door that creates an airtight and secure seal when it is closed. An example on how the inner mechanism of a hemretic door is shown in Figure 40. As suggested in Section 4.1.1, a 10 cm gap between the pod and the airlock chamber walls, will also work for a twin airlock system as this allows for sufficient safety while staying above the radius determined by the Kantrowitz limit. Likewise, a hyperloop system relies on a rail rather than magnetic levitation, the rail gap deemed feasible by Nice Ege will need to be implemented in order to allow the sealant doors to completely cover the airlock chamber without the rail getting in between. As the twin airlock system also relies on turning the pod around, the same features described in the single airlock chamber will need to be implemented namely, the 150 meter circular track or a turntable.

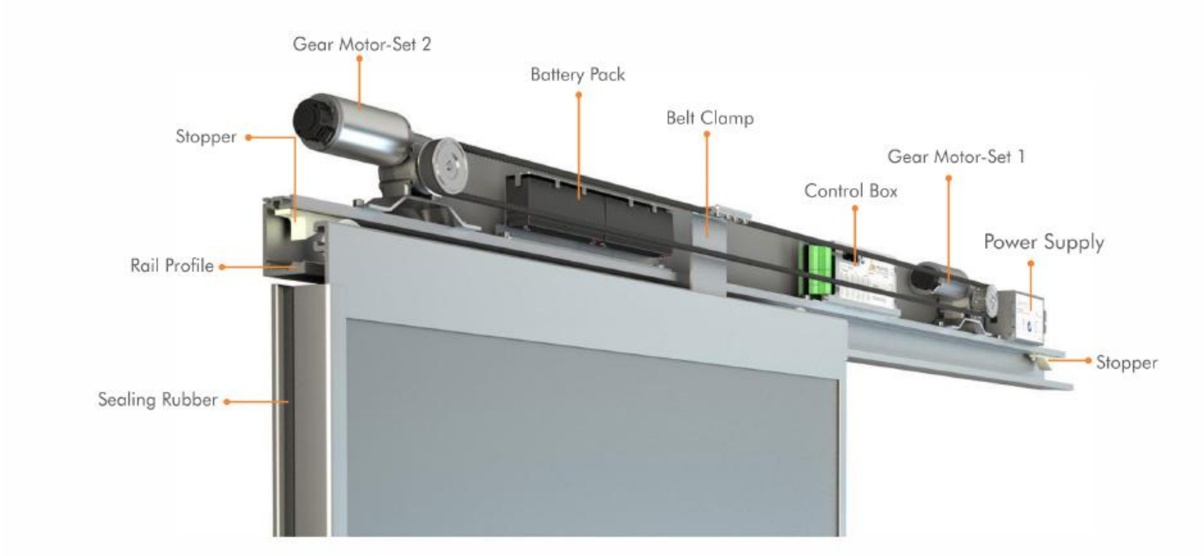

Figure 40: Inner mechanism of a hermetically sealing sliding door, [22]

3.4.2 Advantages and Disadvantages

In regards to emergency airlocks, the twin airlock system is preferable. Since the emergency airlock will be spaced across the length of the tube, it will only be used by pods traveling in the direction of the tube it is attached to. This means that if an airlock chamber is chosen to act as the emergency airlock, it would be a twin airlock as it would not necessarily need to depressurise as it may be necessary to remove the airlock from the chamber entirely. In addition, as the twin airlock chamber allows for fast disembarkment once through the chamber, and is relatively simple to implement, it will likely be the preferable option over end-door airlocks and bridge-door airlocks for emergency stations [17].

Twin airlock chambers, while having their advantages, also come with a few disadvantages that questions the efficiency of the system. The most significant disadvantage of the system would be its high construction and maintenance. Since two separate airlock chambers are required to operate this system, more resources and equipment will be required, raising the total expense of the whole hyperloop system. For instance, a twin airlock system will require more vacuum pumps since two airlock chambers are being repressurised and depressurised. Therefore, the increase in cost comes not just from the additional equipment, but also from the high energy consumption of the system due to the additional cycle of depressurising and repressuring the airlocks.

In addition to its cost, the whole system also takes up more physical space than a single airlock chamber. This additional space is significant to ensure proper planning and smooth operation of both airlock chambers. Hence, this airlock design may not be a viable option for areas with limited space or if the station were to be built underground.

One of the riskiest disadvantages of the twin airlock chambers is the potential human errors due to the complexity of the operation of the system. Operating the system requires a high degree of synchronisation and intricate management of the pods and personnel, which presents many opportunities for accidents to occur. Furthermore, due to this, the system is less efficient as the synchronisation of the pods may extend the waiting time. Since operating the system requires a lot of care, it is recommended that only a few pods are discharged for use as more pods in operation would require more attention. However, this may decrease the frequency of pods coming in and out of the station, and hence, further decrease the efficiency of the system.

Additionally, the complexity of operating twin airlock chambers can lead to potential human errors.

The need to synchronize the operation of two chambers and manage the movement of personnel or objects between them introduces an increased risk of accidents or mishaps. Lastly, the redundancy of having two chambers might be unnecessary in certain scenarios, adding unnecessary complexity to the overall system. Evaluating the specific requirements and considering these disadvantages is essential to determine whether a twin airlock chamber is the most suitable option for a particular environment or application.

3.4.3 System Efficiency

Following the processes laid out in Section 4.1.3, a time of roughly 100 seconds between the pods arrival and departure with a safety gap of 10cm on either side can be achieved. However, because this brings up the need to (de)pressurize the empty airlock chamber in order for the following pod to enter, there is a significant disadvantage for both time and energy. Without the presence of the pod in the airlock chamber, the volume of air that needs to be (de)pressurized is approximately 127 m^3. This large volume results in a depressurizing time of approximately an hour and fifteen minutes and a pressurizing time of an hour and forty-five minutes. This was determined using the same methods as the single air chamber time efficiency. Given that the maximum possible frequency of pods in a hyperloop is once every three minutes, a station made of twin airlock chambers will need 25 arrival airlock chambers and 38 departure chambers in order to ensure an efficient system [79,80]. This implies that a twin airlock system will be a far costlier system when compared to other varieties.

3.5 Safety Regulations and Procedures

In the event of the airlock door failing to latch or seal around the entryway, it is necessary to have a backup door that will be able to seal over this. The design, which incorporates varying pod lengths, has completed this task; should one of the inner doors fail, a pair of doors designed for a longer pod shall activate, acting as an emergency airlock. The airlock must therefore have at least one more pair of doors than there are pod lengths, to have an emergency door for the longest pod length. Similarly, the station should have backup vacuum pumps that will be used only in emergencies, in case of a failure to depressurize.

Furthermore, should a station elect to use another airlock system, implementing a single air chamber as an emergency airlock would be the most effective method. This is because a single air chamber should be able to encapsulate any of the smaller airlock designs such as bridge doors. Similarly, it is necessary to have emergency airlocks along the tube; a single air chamber is recommended for this as it requires less mechanism and each emergency airlock will be attached to a unidirectional tube therefore a twin airlock will not be necessary.

One issue to take into account when analyzing the safety of the system is thermal expansion. Assuming a temperature difference of 30°C between winter and summer in the United Kingdom, the concrete the airlock is made of will expand by approximately 2.6 centimeters; therefore the proposed gap of 10 centimeters will accommodate for thermal expansion in the summer months [83]. Furthermore, as the airlock will be in close proximity to the station, the airlock can be temperature-controlled to prevent thermal expansion of the rail and concrete. Moreover, Network Rail currently uses remote monitoring systems that alert them if any section of the rail expands too much and poses a threat to the train; while thermal rail expansion poses less of a threat to a hyperloop, due to the rail being insulated and not exposed to direct sunlight, similar systems could still be used as a safety precaution.

One aspect of the hyperloop that should not be neglected is the perceived safety. As discussed before, a lack of perceived safety of a system will result in less usage thus, reducing the economic benefit of the hyperloop [77]. As shown by Schneider et. al, perceived safety at a train station decreases as perceived crowd density increases [84]. Hence, the design of the airlock should therefore aim to reduce crowding in the hyperloop, especially during peak travel hours. This will result in less risky behavior taken by hyperloop passengers, reducing the number of incidents that occur and thus reducing the hesitancy surrounding the form of transport [84]. Due to the proposed demand for a hyperloop, it is necessary to automate some safety regulations to support the large number of consumers. Alawad, An, and Kaewunruen demonstrated the usage of an Adaptive neuro-fuzzy inference system in assessing the level of overcrowding risk in railway systems [85]. This system analyzes crowds in the station and provides real-time data to station administration [85]. Implementing such a system in a hyperloop station will allow us to increase the effectiveness of anti-overcrowding measures and promote overall safety surrounding the hyperloop.

As the hyperloop is a relatively new mode of transportation, there does not exist much public media surrounding the subject. Kang and Kim demonstrated in their paper that Youtube content promotes trust among viewers through the trust transfer theory [78]. This means increasing the amount of content regarding the hyperloop, will result in an increased perceived safety as people will develop more trust in the system due to the abundance of advocating media surrounding it. In addition, since the airlock is a crucial part of the hyperloop, companies should aim to create media surrounding the mechanisms of the airlock, to increase confidence in the system among consumers and reduce the fear surrounding the concept.

3.6 Comparison of Airlocks

Table 7: Comparison of Single Air Chamber, End-Door Airlock, Bridge Doors Airlock, Twin Airlock Chamber

Comparison of the different airlocks		
Airlocks	Main advantages	Main disadvantages
Single Air Chamber	• No need to depressurize an airlock without a pod inside of it, reducing the amount of pumping required, and hence, allows for lower energy consumption. • The most simple airlock system and hence, requires the least maintenance which reduces costs.	• Lower efficiency as the incoming pod is required to wait for the previous pod to complete its entire station cycle before the incoming pod can enter the airlock. • Requires a significant amount of space if the pod is required to be rotated.
End-Door Airlock	• No need to repressurize a significant portion of the tube in order to allow the boarding and exit of passengers. • Available technology that has been implemented in space shuttles and hence, has a lower risk for the safety of the passengers. • No need to seal off a section of the tube, and hence, there are no complex moving parts.	• Requires additional physical space within the tube to allow for the opening of the pod at the end of the stations, which may be difficult to construct in limited spaces like underground.
Bridge Doors Airlocks	• Time-efficient due to the small volume required to be depressurised, which reduces pump down time. • Allows for a smoother process of boarding and exiting of passengers in and out of the pod.	• Greater complexity in its design, increasing the cost of the construction of the system. • Requires extreme precise monitoring and more maintenance. • Greater risk of pump failure due to the increased number of connections they are required to have as they are connected to multiple bridge doors.
Twin Airlock Chambers	• Allows for simultaneous pod entry and exit, and hence leads to a faster disembarkation process. • Very efficient as an emergency airlock system for evacuation.	• Requires a significant amount of physical space for operation, hence not a good option for areas with limited space. • Operation of the system is very complex as it requires a certain degree of synchronisation. • Inefficient if the synchronisation of the system is not up to standard.

Choosing the best airlock to implement depends on multiple factors such as the amount of available space, budgeting and the expected level of performance. For instance, based on the summary in Table 7, if a simple system was desired, the best choice of airlocks would be the single air chamber as it has the least complex operating system. To increase the frequency of pods and maximise the rate of passengers in and out, the twin airlock chambers design would be the most well-suited airlocks.

However, the optimum choice for an airlock would be well-balanced in all of these aspects, and hence, it would be the end-door airlock system. The major reasoning behind this is because it is considered as a tried and tested technology as it has already been implemented in the space industry. Hence, while it is a more complex system than the single air chamber system, since it has already been put in practice, there should be fewer complications in constructing and maintaining the system. In addition to this, the end door airlock system is efficient in terms of providing a smooth entry and exit process for passengers. A smooth entry and exit process is crucial especially in times of emergency whereby passengers may be required to evacuate the pods and the station. If it is as efficient as it is during an emergency, this also removes the need of having an additional airlock system as a back up, further reducing costs. It is recommended that further research should be done to test this theory by modeling the system and simulating different scenarios.

4 Conclusion

After investigating into the performance of different has displacement pumps and airlock systems, several findings have been highlighted. First and foremost, it is recommended for a vacuum management system for a hyperloop, that an end-door airlocks system is implemented, which utilitises a combination of roots and rotary vane pumps to repressurise and depressurise the airlocks. Roots pumps were determined to be the most efficient vacuum pumps when compared to rotary vane and liquid ring pumps, but are still inefficient if they were the sole pumps used in a hyperloop system. Hence why it is proposed that they are used alongside rotary vane pumps serving as backing pumps. More research needs to be undertaken to ascertain the economic benefits and the best arrangement for this combination of vacuum pumps. This paper also determines the end-door airlocks to be the most well-balanced airlocks in terms of maintenance, complexity and efficiency. It is considered as reliable technology due to the practice of its technology in the space industry, and hence, even if it may be more complicated than a single air chamber, its construction and maintenance should still have lower risks of encountering unknown errors. However, it still has certain drawbacks such as only having one single entry and exit point, which can result in a mismanaged flow of passengers, especially in emergencies. This aspect could be modified by modifying the airlocks to increase the number of its exit and entry points using bridge doors, but this modification also brings in more complications. Overall, the recommended system requires further research, including simulations of the system, to test its feasibility and effectiveness, and be compared to other combinations of airlocks and vacuum pumps.

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