QUARTZ: HYPERLOOP TO THE MOON
DESIGNING A VACUUM PUMP SYSTEM FOR THE HYPERLOOP

Ganesh B
CH22B002

ABSTRACT

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 the possible methods and modifications to optimise the performance of vacuum pumps and airlocks when being implemented in a hyperloop system, especially keeping in mind the astrophysical conditions. 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, the material design of the pump components for withstanding the atmospheric conditions that vary significantly from the surface of the earth, to space and finally to the moon surface is also discussed. This includes studying multiple sources of leakage which would lead to the failure of the vacuum and the corresponding solutions to mitigate them.

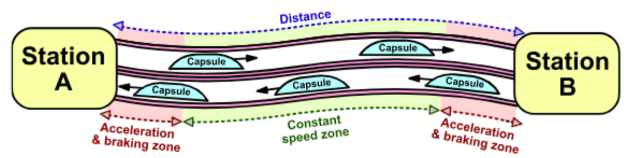

FIGURE 1: Sketch of a conceptual HTS diagram depicting passenger capsules' movement inside a two-way tunnel

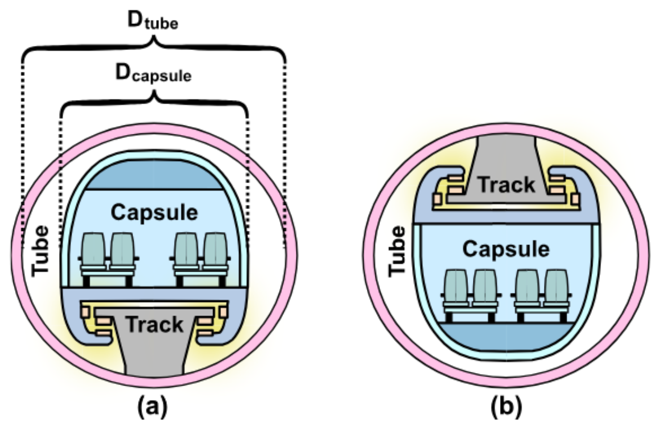

FIGURE 2: Generic illustration [3] of the HTS concept, including the tube, the capsule, and a wide track (seen perpendicular to the moving direction). The tube's inner diameter and the capsule's outer diameter are also indicated. a) Vehicle floats on the track. b) Vehicle hangs underneath the track.

Introduction to Hyperloop

The Hyperloop Transportation System (HTS) is a modern high speed transport, offering the potential for near sonic travel by operating in a low pressure tube (almost vacuum) environment. Unlike conventional rail systems, Hyperloop minimizes aerodynamic drag and friction losses by using magnetic levitation and vacuum-based infrastructure.

Although still in the experimental phase, HTS is considered one of the fastest conceptual methods for traversing Earth's surface, surpassing the speeds of even high speed rail and short haul aviation. However, scaling such systems to operate at practical speeds in large-scale implementations presents a ton of challenges. These include sustained depressurization of the travel tube, control of choked flow conditions near the capsule, airlock integration, and the trade-off between infrastructure size and energy efficiency.

Extending the Hyperloop paradigm beyond the Earth, to the Moon is a humongous challenge. It requires us to address the requirements of a modular, self-contained propulsion units, magnetic levitation for frictionless travel, and staged vacuum pumping systems to maintain ultra-low pressure conditions along the length of the transit tube, in astrophysical scales, sustaining the extreme conditions of outer space.

Design of Pump for Sustained Vacuum Environment

In a hyperloop system 3, 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 ecient to minimise power consumption

Additionally for long range travel from earth to moon, we shall extend the periodic installment of pumps along the tube just like it is done usually. However, we will have to consider the atmospheric and radiative conditions of outer-space in the material design. We will discuss this in the later sections.

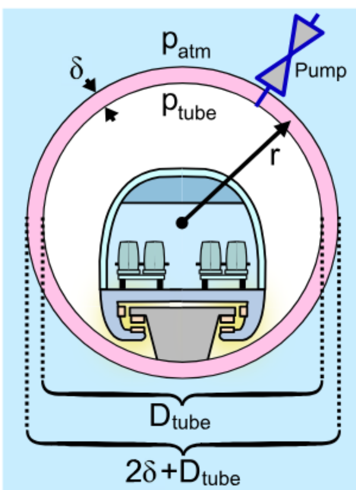

FIGURE 3: Sketch depicting the main geometrical parameters determining the performance of the evacuation system. The pressure inside the tube (P_{tube}) is evacuated by a tube wall of thickness δ. The pump depicted has a nominal power rating of P_{pump}. It is responsible for tube depressurization, as well as compensating for air leakages under operation. The number of pumps is N_{pump}, and they are uniformly distributed along the tube trajectory

Types of Pump

Overall, vacuum pumps are divided into two main types: gas transfer and gas binding vacuum pumps as shown in Figure 4. The vacuum pumps of interest are roots pump, rotary vane pump, and liquid ring pump, which are gas displacement pumps. The analysis for various pumps performed by our own institutes hyperloop team Avishkar, is below:

1. **Rotary Vane**: Suitable for the pressure range, but has low pumping speeds.
2. **Scroll**: Adequate pressure range but poor pumping speeds.
3. **Diaphragm**: Ineffective in pressure range and pumping speeds.
4. **Diffusion**: Requires rotary pumps; low pump speed.
5. **Roots Blower**: Used as a backing pump; not for primary vacuum creation.
6. **Dry Screw, Liquid Ring, Rotary Piston**: Suitable for both pressure range and high pumping speeds.
7. **Sputter Ion**: Ideal for ultra-high vacuum.
8. **Venturi**: Not suitable for the required scale.
9. **Multistage Roots**: Suitable for both pressure range and high pumping speeds.

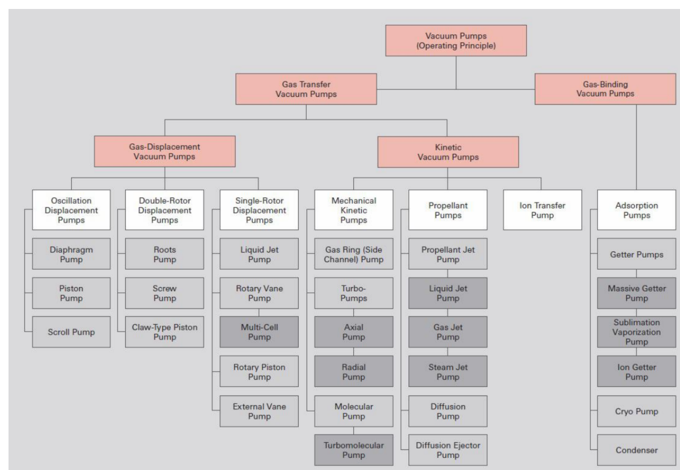

FIGURE 4: Types of Vacuum Pumps

Roots Pump

A roots pump consists of two parallel, interlocking rotors known as the male and female rotors labelled as number 4 in Figure 5. These rotors are uniquely shaped, resembling figure-eight lobes. Encased within a housing, the rotors rotate in opposite directions while maintaining synchronous motion. 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 5. 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.

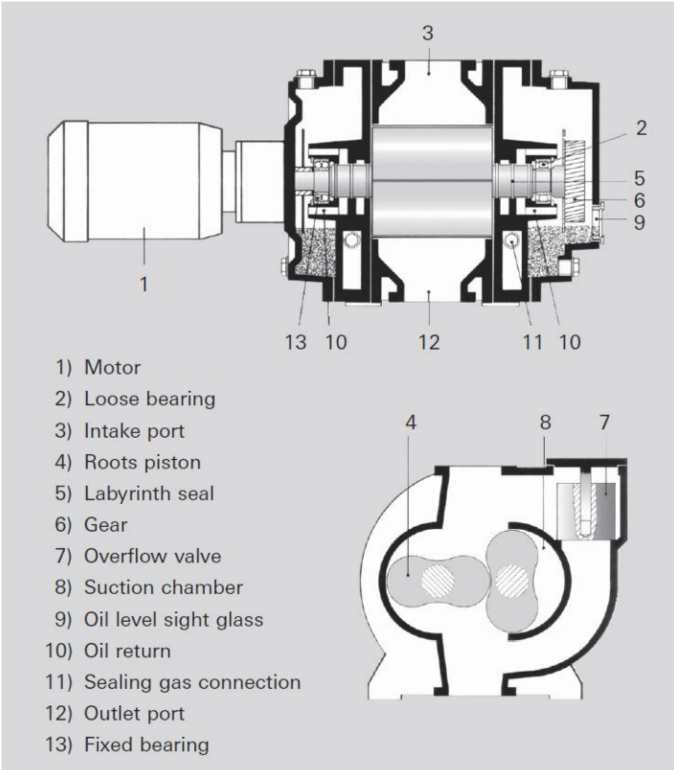

FIGURE 5: Root Pump Inner and Outer Structure

Rotary Vane Pump

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 6, 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

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

Material Design of Pumps

There are two important aspects to the material deign of the pump system. One is the internal modules and pump components, and the other the housing, outer casing, and seals. Let us analyze them one by one. There is also the problem of need of vacuum over an extremely large distance of $3,84,400$ km. This would mean usage of tremendous amounts of energies for the pumps periodically placed along the tube. However, we shall not concern ourselves with this since it is not a material design problem.

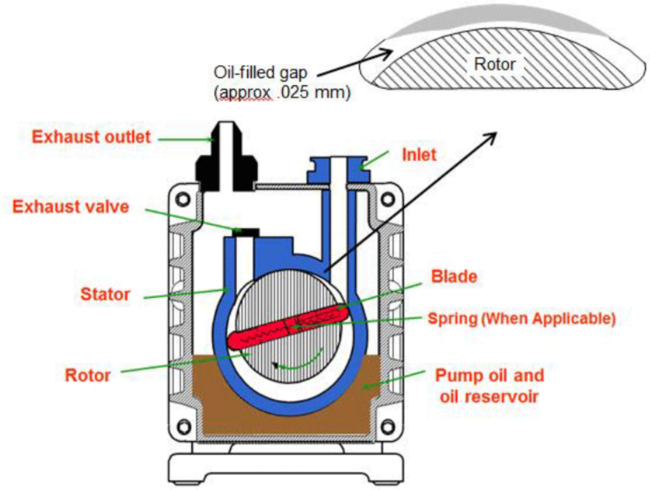

FIGURE 6: Cross-sectional view of a rotary vane pump

To evaluate material suitability for a space-adapted Hyperloop vacuum pump system (roots and rotary vane pumps), we must distinguish between the environmental demands of two key segments of travel: Surface to Low Earth Orbit (LEO) and LEO to the Moon. The earlier tables outlined specific materials for both external (housings and seals) and internal components (rotors, vanes, bearings). Below is a detailed comparative analysis of how those materials perform in each travel segment.

Surface to Low Earth Orbit

The surface-to-LEO phase exposes all components to atmospheric pressure, mechanical vibration, acceleration forces, and moderate thermal gradients. The system must handle:

1. Full atmospheric pressure at sea level transitioning to near-vacuum
2. Temperatures ranging from -50°C (at high altitudes) to 100°C (due to friction and heating)
3. Moderate radiation exposure (some shielding from Earth's magnetosphere)

External Components:

Titanium Ti-6Al-4V is optimal for pump housings in this segment. Its superior strength-to-weight ratio allows the system to endure mechanical stresses from launch and acceleration without adding significant mass. Titanium's corrosion resistance also ensures structural longevity during long periods of pre-launch exposure to humidity and contaminants.

Aluminum alloys, such as 7075-T6, are also viable due to their lightweight nature, but they are less resistant to corrosion and fatigue. Hence, aluminum is better suited to internal structures or housing components with limited exposure to moisture and chemical interactions.

Seals in this segment must handle pressure differentials and mechanical vibration. PTFE (Teflon) seals perform adequately due to their chemical inertness and flexibility, although they tend to deform under prolonged load. For high-performance applications, especially near the vacuum end of the tunnel, **Kalrez** (FFKM) seals are preferable due to their low outgassing, radiation resistance, and broad thermal stability, albeit at a higher cost.

Internal Components:

Carbon fiber composites for rotors are especially suited for this segment due to their lightweight and high stiffness. The low inertia helps maintain high RPMs while keeping the load on motors manageable. However, composites require precise fabrication and are more brittle under impact loads, making them susceptible to launch-induced shock unless reinforced.

Alternatively, titanium rotors offer superior robustness, making them a conservative choice where mechanical integrity is prioritized over minimal weight.

Graphite-impregnated resin vanes are efficient in Earth's atmosphere and early ascent phases because they are self-lubricating and can tolerate brief contact with moisture or particulates. However, these materials are sensitive to outgassing and thermal degradation in space.

Bearings during this phase can still rely on steel (52100), as traditional lubrication remains feasible at higher pressures. However, where transitioning to vacuum conditions is anticipated (e.g., at high altitudes or in sealed launch tubes), hybrid ceramic bearings (steel races with silicon nitride balls) provide a smoother transition to space-compatible performance, resisting thermal and frictional degradation.

Low Earth Orbit to Moon

Once in LEO and beyond, the operational context changes dramatically. This segment involves:

1. Intense radiation (solar and cosmic rays)
2. Extreme thermal gradients (from -150°C in shade to +120°C in sunlight)
3. No atmospheric conduction or convection for heat transfer
4. No opportunity for fluid-based lubrication

External Components:

In this vacuum and high-radiation environment, **Inconel** 718 surpasses titanium in many respects. While heavier, it offers extraordinary thermal stability, oxidation resistance, and strength retention at high temperatures — critical for hardware exposed to both solar radiation and internal pump heating.

For long-duration use in deep space, **Kalrez** seals become indispensable due to their resistance to radiation-induced embrittlement and outgassing. **PTFE**, though useful at lower costs, can become brittle and leak in UHV conditions and is not suitable for mission-critical seals over lunar transfer durations.

Internal Components:

Carbon fiber composites remain excellent for rotors because of their dimensional stability and minimal thermal expansion — important in a vacuum where materials cannot easily shed heat. However, they must be specially treated or combined with metallic hubs or faces to resist radiation degradation.

Silicon carbide (SiC) emerges as a standout material for rotary vanes in this environment. It resists wear without requiring lubrication, remains dimensionally stable across vast thermal cycles, and does not outgas — essential in a vacuum. In contrast, graphite-based vanes would erode quickly and contaminate the vacuum.

Boron nitride vanes are also highly suitable, offering self-lubricating properties and radiation resistance, although they are somewhat softer and may erode more quickly than SiC in high-load systems.

Bearings must be fully **ceramic** (e.g., Si_3N_4) in this segment, as conventional steel bearings with lubricants will seize due to evaporation and molecular breakdown. Full ceramic bearings can operate in dry environments, tolerate significant thermal cycling, and exhibit minimal outgassing, ensuring long-term functionality with reduced maintenance.

Synergy and Interaction with Other Hyperloop Components

Although the design of vacuum pumps is irrelevant to other systems, the vacuum maintained affects the design of the capsule (pod) and the outer tube. The material design of both of these are covered extensively by Dev and Suresh. Therefore we will explore an interesting component: the design of a compressor system for the pod, which assists the almost vacuum fluid flow in moving even faster, considering the scale of travel to the moon.

Need for a Compressor

For high-speed ground transportation, particularly in tunnel environments where compressible flow phenomena like shock waves and flow blocking can occur. For hyperloop systems operating entirely in enclosed tubes, these effects persist throughout the entire journey. Tunnel size becomes a critical factor as it directly impacts infrastructure costs : reducing the tube diameter while maintaining vehicle cross-section leads to exponential increases in power consumption and exceeding something called

TABLE 1: Material Comparison for External Components of Space-Ready Vacuum Pumps

Component	Material	Density (g/cm^3)	Temp Range (°C)	Justification
Housing	Ti-6Al-4V	4.43	-250 to 400	High strength-to-weight ratio, excellent corrosion resistance, suitable for aerospace applications [1].
Housing	Inconel 718	8.2	-250 to 700	Superior mechanical properties over a wide temperature range, excellent oxidation and corrosion resistance [5].
Seals	Kalrez (FFKM)	1.98	-20 to 250	Retains good physical properties at high temperatures, resistant to chemicals encountered in harsh environments [6].
Seals	PTFE	2.2	-200 to 260	Chemically inert, excellent vacuum compatibility, widely used in spacecraft gaskets [7].

TABLE 2: Material Comparison for Internal Components of Space-Ready Vacuum Pumps

Component	Material	Density (g/cm^3)	Temp Range (°C)	Justification
Rotor (Roots)	Carbon Fiber Composite	$\sim$1.6	-200 to 300	Lightweight, high strength, thermally stable, minimal expansion under thermal loads [8].
Rotor (Roots)	Ti-6Al-4V	4.43	-250 to 400	High mechanical strength, low wear, non-magnetic, radiation-hard [1].
Vane (Rotary)	Silicon Carbide (SiC)	3.2	-200 to 1600	Exceptional hardness, high thermal resistance, vacuum stability, self-lubricating [9].
Vane (Rotary)	Boron Nitride	2.1	-200 to 1000	High wear resistance, radiation-tolerant, good for dry-running pumps [10].
Bearings	Si_3N_4 (Ceramic)	3.2	-200 to 800	No lubrication needed, low thermal expansion, high stiffness, ideal for vacuum and cryogenic applications [11].
Bearings	Hybrid (Steel/Si_3N_4)	$\sim$4.5	-200 to 300	High load capacity, reduced thermal load, used in aerospace for reliability [11].

the Kantrowitz limit. The Kantrowitz limit refers to the maximum allowable pressure ratio across a constriction (like a nozzle or inlet) beyond which a normal shock will form, preventing further increases in mass flow rate. In essence, it determines the choking condition of flow in a duct or tube.

To understand the flow mechanisms, we look at the CFD simulations performed by Rodriguez et al. [4]. The setup is as defined in 7 and the boundary conditions is as follows:

Boundary Conditions and Parameters

The following boundary conditions and parameters are defined:

Inlet: The mass flow $\dot{m}_{ref}$ and total temperature $T_{t,ref}$ are imposed. Both are based on:

Capsule speed V_{ref}
Reference pressure p_{ref}
Static temperature T_{ref}
Tunnel area $\pi h^2/\beta$

$$\dot{m}_{ref} = \frac{p_{ref}}{RT_{ref}} \frac{\pi h^2}{\beta} V_{ref} T_{t,ref} = T_{ref} + \frac{V_{ref}^2}{2c_p}$$

Tube: Moving and adiabatic wall. The wall speed equals the capsule speed V_{ref} in a ground reference frame.

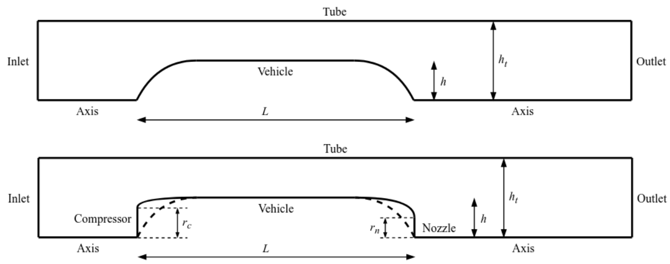

FIGURE 7: a)Pod without a compressor b) Pod with a compressor system at the front

Outlet: Pressure outlet, set to the tube reference pressure p_{ref}.
Vehicle: Static and adiabatic wall.
Axis: Rotation axis to convert the 2D domain into axisymmetric.
Nozzle: Mass flow inlet. The mass flow $\dot{m}_c$ is imposed such that:

Turbomachinery swallows $\dot{m}_c$
Total temperature at nozzle exit is $T_{t,n}$

(Values discussed in Section 2.6)
Compressor: Pressure outlet, adjusting pressure until obtaining the nozzle mass flow.

Parameter Values

The simulation uses these parameter values:

Reference speed V_{ref}:

500 km/h (current limit for Transrapid [?])
700 km/h (higher speed considered for hyperloop)

Reference pressure p_{ref}: 0.1 atm
Blockage ratio β: 0.2 to 0.75
Reference temperature T_{ref}: 288.15 K (same as [?])
Turbulence intensity: 5%

Results of the Analysis

The addition of the compressor significantly increases the axial velocity at the turbine plane, leading to higher energy capture.
The pressure drop is slightly higher in the compressed configuration due to increased acceleration and area contraction.
The power coefficient (C_p) shows an improvement of approximately 50%, indicating enhanced performance.
Overall, the compressor improves the aerodynamic efficiency and flow characteristics within the duct.

We observe that the as the size of the tube increases, undesirable shocks are observed in the non-compressor case. This is avoided largely in the compressor case. This is necessary because size of the tube vastly affects the cost of construction of the hyperloop, especially when we use high performance materials for such a large scale from the earth to the moon.

TABLE 3: Comparison of CFD results with and without compressor

Parameter	Without Compressor	With Compressor
$V_{\text{axial max}}$ (m/s)	7.15	9.22
Pressure Drop	143.2	175.6
C_p	0.265	0.398
$V_{\max}/V_{\text{inlet}}$	1.43	1.84
$\dot{m}$	0.912	1.214

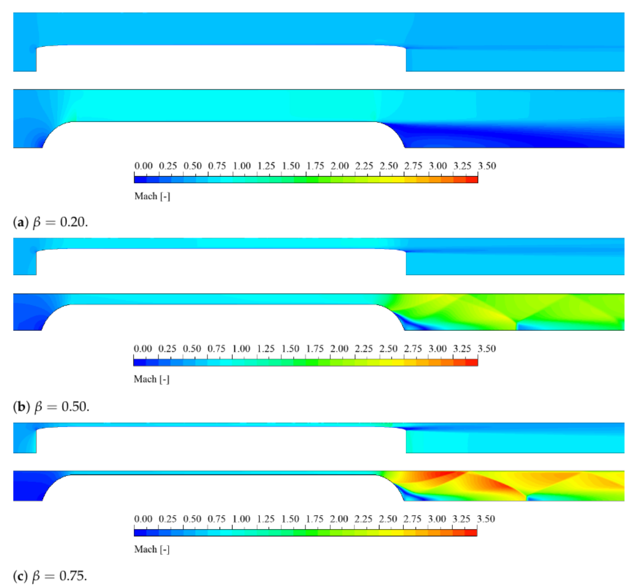

FIGURE 8: CFD Simulation Results, comparing different βs for the compressor and non compressor cases. In each case, the upper one shows the effects of the compressor

Conclusion

The successful realization of a Hyperloop system extending from Earth to the Moon hinges on the development of a highly efficient, resilient, and scalable vacuum infrastructure. We examined the design, performance, and material considerations of vacuum pumps suitable for such an ambitious transit system, focusing on roots and rotary vane pumps. Through comparative analysis, it is evident that materials like Inconel 718, Kalrez seals, carbon fiber composites, and silicon carbide vanes offer the optimal balance between mechanical performance, radiation resistance, and vacuum stability required for extraterrestrial operations. As demonstrated, the design of vacuum systems must be harmonized with other critical subsystems—such as pod propulsion and structural components—highlighting the interdependent nature of Hyperloop engineering at astrophysical scales. While most of this is still pie in the sky, we hope that someday we will be equipped with enough technology to implement this.

Attestation

Peer 1 : Dev Joshi, CH22B061 I attest that Ganesh has done his part on the design and analysis of the Vacuum Pump system for our group.

Peer 2 : Suchir, CH22B105 I attest that Ganesh has done his part on the design and analysis of the Vacuum Pump system for our group.

Peer 3 : Suresh, CH22B042 I attest that Ganesh has done his part on the design and analysis of the Vacuum Pump system for our group.

Peer 4 : Ashwin, CH22B025 I attest that Ganesh has done his part on the design and analysis of the Vacuum Pump system for our group.

REFERENCES

[1] Carpenter Technology Corporation. *Titanium Alloy Ti 6Al-4V - Data Sheet*. Retrieved from `https://www.carpentertechnology.com/hubfs/7407324/Material%20Saftey%20Data%20Sheets/Ti%206Al-4V.pdf`

[2] University of Edinburgh Integration and performance study of vacuum pumps and airlocks in a hyperloop system

[3] Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review `https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9350309`

[4] CFD Simulation of a Hyperloop Capsule Inside a Low-Pressure Environment Using an Aerodynamic Compressor as Propulsion and Drag Reduction Method `https://doi.org/10.3390/app11093934`

[5] Special Metals Corporation. *INCONEL® Alloy 718 - Technical Bulletin*. Retrieved from `https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-718.pdf`

[6] DuPont. *Kalrez® Perfluoroelastomer Parts - Product Selector Guide*. Retrieved from here

[7] SPACEMATDB. *PTFE - Space Materials Database*. Retrieved from `https://www.spacematdb.com/spacemat/datasearch.php?name=PTFE`

[8] ScienceDirect. *Radiation resistance of carbon fiber-reinforced epoxy composites*. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1359836818334413`

[9] Accuratus Corporation. *Silicon Carbide SiC Material Properties*. Retrieved from `https://accuratus.com/silicar.html`

[10] Wikipedia. *Boron nitride*. Retrieved from `https://en.wikipedia.org/wiki/Boron_nitride`

[11] FHD Bearings. *The Ultimate Guide To Si3N4 Ceramic Bearings*. Retrieved from `https://fhdbearings.com/blog/si3n4-ceramic-bearings/`