AN AUTONOMOUS HYPERBARIC CHAMBER, OR A HYPERLOOP TUBULAR RAILWAY CAPSULE

Andrzej Krzyszkowski[1)], Piort Siermontowski [2)], Jacek Zboina[3)]

[1)] Casimir Pulaski Radom University, Radom, Poland
[2)] Department of Underwater Works Technology, Polish Naval Academy, Gdynia, Poland
[3)] Scientific and Research Centre for Fire Protection - NationalResearch Instytute, Poland

ABSTRACT

The authors conducted a comparative analysis of a high-speed transportation system—commonly referred to as the Hyperloop tubular railway—and a hyperbaric chamber as well as an aircraft cabin, with respect to differential pressure magnitudes and the associated technical and medical hazards that significantly affect passenger safety.
The study examined fundamental systems and technical solutions governing pressure modulation, the composition of breathable air, the airflow required for capsule propulsion, and passenger protection. The analysis demonstrated the functional independence of these subsystems, confirming the capsule's autonomous operational characteristics.
Furthermore, similarities arising from internal pressure differentials within the Hyperloop capsule and those observed in hyperbaric chambers and high-differential-pressure aircraft cabins were identified.
Keywords: hyperbaria, transportation, medicine, safety, engineering, tubular railway.

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INTRODUCTION

The Hyperloop tubular railway concept assumes the movement of a passenger capsule within a sealed tube. Inside the tube, the pressure is reduced to approximately 100 Pa [1,35], which corresponds to about 0.0001 of atmospheric pressure at sea level. Within the capsule—the actual transport vehicle—the pressure is intended to be maintained at approximately 1 atm (100,000 Pa).

The capsule moves autonomously on a magnetic levitation system, employing both magnetic levitation and air bearings, which are more advantageous in operation—both technically and economically—compared with conventional railway solutions. The capsule is propelled by linear motors. A functional diagram of the propulsion and movement process is presented in Fig. 1.

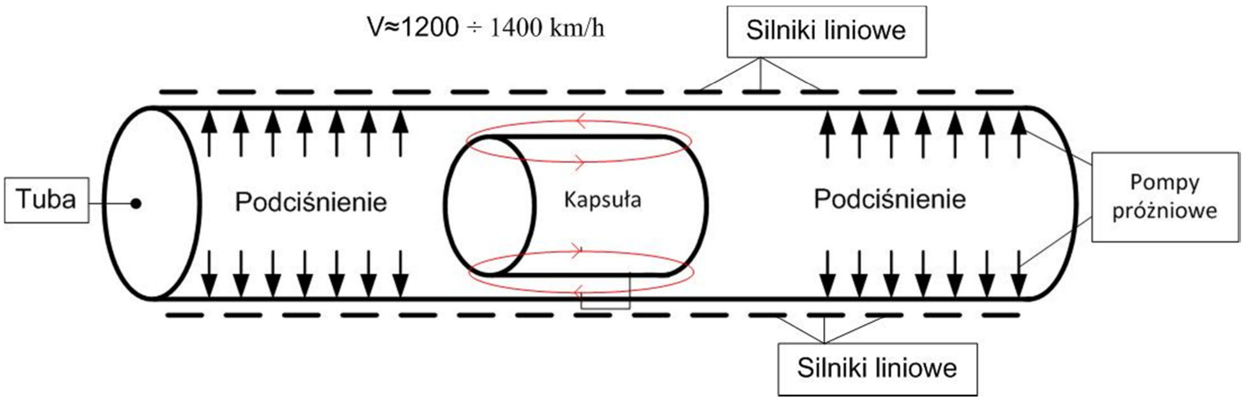

Fig. 1 Schematic representation of capsule motion within the tube [4].

Such a substantial pressure differential between the interior of the capsule and its exterior within the tube provides a technically justified basis for comparing the system to a hyperbaric chamber, where internal pressure is elevated several-, a dozen- or even several dozen-fold relative to the ambient environment. The analogy is even closer to that of a high-differential-pressure aircraft cabin, in which the internal pressure corresponds to an altitude of approximately 2,000–3,000 meters above sea level, while outside the aircraft—at the standard cruising altitude of jet-powered aircraft of around 11,000 meters— the ambient pressure is 226 hPa. Given the sea-level standard pressure of 1013 hPa, this results in a four-fold differential, whereas within the proposed HYPERLOOP system the difference reaches a factor of one thousand.

Preliminary analysis reveals both the magnitude of the pressure differentials and the enforced autonomization of the capsule in comparison with a hyperbaric chamber or an aircraft cabin, as well as the distinct placement of the technical equipment required to ensure the reliable operation of each of the examined systems, all of which maintain internal pressures significantly higher than the external environment. The pressure differentials observed in the capsule, relative to other habitable enclosures, necessitate the use of the most advanced engineering solutions—referred to by many research centers and by the designers themselves as "space technologies". For this reason, the comparison must be conducted within a framework different from classical hyperbaria or hypobaria, even though the scientific problem naturally falls within this broader domain.

ASSUMPTIONS OF THE HYPERLOOP TUBULAR TRANSPORT PROJECT

Tubular transport concepts developed in the United States (by SpaceX, with Elon Musk as the principal stakeholder) under the name HYPERLOOP envision, according to the 2015 design study, the construction of two lines [1,3]:

- Los Angeles – San Francisco**,**
- New York – Philadelphia**,**

which are intended to employ analogous technical and structural solutions. The internal diameter of the passenger–freight tube has been optimized—based on technical, structural, and operational criteria—to 3.30 m**,** resulting in a cross-sectional area of 8.55 m^2**.**

GENERAL CAPSULE DESIGN

Two configurations are proposed: one dedicated to passenger transportation and the other to freight transport.

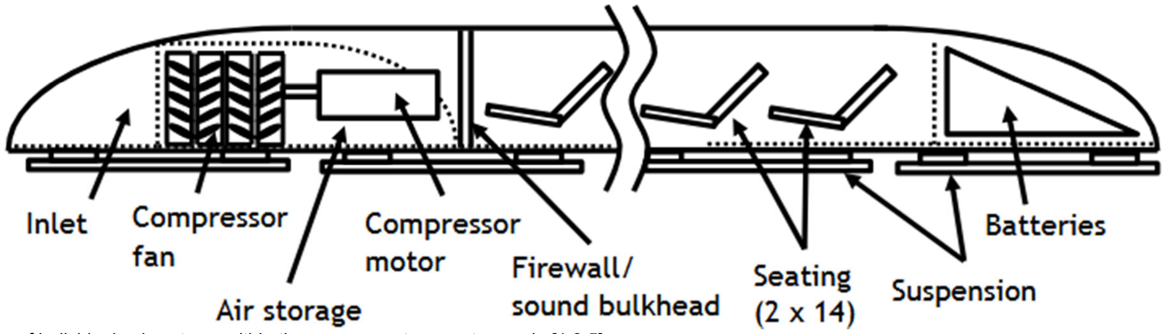

Fig. 2 Location of individual subsystems within the passenger-transport capsule [1,3,5].

The geometry of the capsule has been designed to optimize its speed and operational efficiency under the assumed preliminary parameters—the frontal cross-sectional area has been minimized as far as possible while preserving passenger comfort and ensuring adequate interior space.

BASIC CAPSULE PARAMETERS

- Approximately 40% of the residual air within the tube is compressed by the axial compressor at a 20:1 compression ratio.
- The remaining 60% of the air flows through narrow ducts along the lower part of the capsule toward the rear section.
- A rear nozzle expands the passing airflow to mitigate part of the residual aerodynamic drag resulting from the pressure differential ahead of and behind the capsule, as well as the bearing drag.
- Up to 0.2 kg/s of air is cooled and additionally compressed at a 5.2:1 ratio in the passenger-transport version, followed by supplemental cooling, after which it is stored in onboard pressure tanks. The stored air is intended for use by the air-bearing system to maintain the clearance between the capsule and the tube walls [1].
- An onboard water tank supplies coolant for the air-cooling system. Water is pumped at a rate of 0.14 kg/s through two heat exchangers (the total mass of coolant is 290 kg), while the resulting steam is stored onboard until the capsule reaches a station. Both water and steam tanks are automatically replaced at each station.
- The compressor is powered by an onboard electric motor rated at 436 hp (325 kW), with a mass of 169 kg, including associated electronics. It is estimated that the 1,500-kg battery pack can power the onboard compressor for 45 minutes, which exceeds the required duration for the entire journey while also providing emergency power. The onboard batteries are replaced at every stop and recharged at the station [1,3,5].

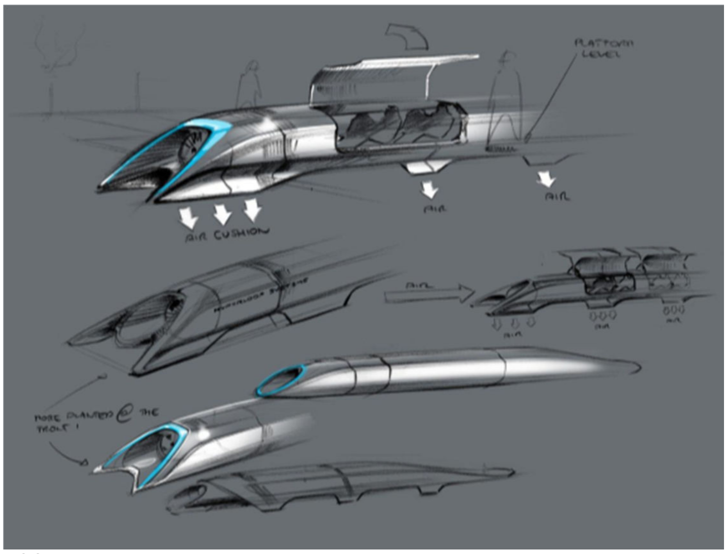

Fig. 3. Conceptual sketch of the HYPERLOOP passenger capsule design [1,3,5].

Aerodynamic power demand at a speed of 700 mph (1130 km/h) is only about 134 hp (100 kW), with a drag force of merely 320 N. The doors on each side will open upward (or, alternatively, slide open) to facilitate easy access during loading and unloading operations. The luggage compartment will be located either at the front or the rear of the capsule.

The total structural weight is expected to be approximately 3100 kg, including the luggage compartment and the door mechanism. The overall construction cost—covering capsule manufacturing without interior components—is estimated at no more than USD 245,000.

The complete interior mass of the passenger HYPERLOOP capsule is expected to be close to 2500 kg, including the seating assemblies, mounting systems, interior door panels, luggage compartment cover, and the entertainment display. The total cost of the interior components is estimated at no more than USD 255,000 [1,3].

Capsule Compressor

The compressor enables the capsule to travel through the relatively narrow tube without choking the airflow between the capsule and the tube walls—a phenomenon that would cause an accumulation of air in front of the capsule, thereby increasing aerodynamic drag. By capturing and compressing the air that accumulates at the capsule's nose, the compressor minimizes this effect. The compressed air is subsequently supplied to the air-bearing system, which maintains the capsule's levitation clearance during travel [1,3]. The air-processing sequence follows the schematic shown in Fig. 4.

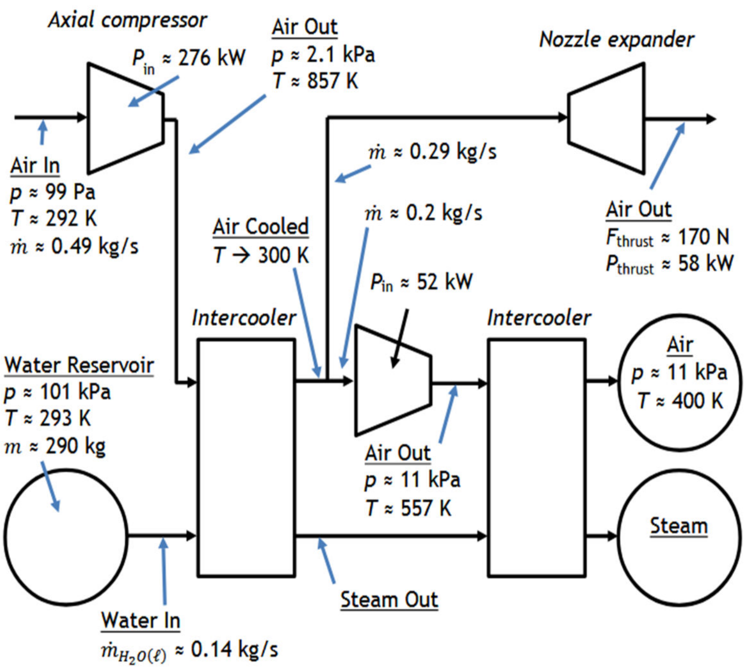

Fig. 4 Operating schematic of the compressor installed in the passenger capsule [1,3,5].

Energy Demand – Solar Power

Solar panels will be installed along the outer surface of the tubes to provide the system with the required energy. This represents an area measuring 6.6 m in width and more than 563 km in length. It is anticipated that the solar panels will generate 120 W/m^2, and that during peak solar activity the system will be capable of producing up to 598,000 hp (446 MW), which is significantly more energy than is required for the operation of the HYPERLOOP system [1].

Technical and Medical Safety of Capsules and Stations

Hyperbaric chambers should be located at the stations, where they would be used for medical and emergency operations in the event of a system failure—specifically, capsule depressurization.Polish engineers and designers have extensive experience in this field, as in the 1970s and 1980s the shipyard in Szczecin produced long-duration "habitats" intended for deep-sea diving teams. At that time, it was one of only three facilities in the world to manufacture such structures largely based on its own proprietary technologies [1,3,5].

This may have significant relevance should attempts be made to implement a tubular railway project in Poland, as the co-authors of this study can be considered natural successors to these technical and medical traditions.

In the event of minor leakage, the onboard environmental control system will maintain the capsule's internal air pressure using its reserve air supply—sufficient for the short period required to reach the nearest station. In cases of more substantial pressure loss, oxygen masks, arranged in a manner analogous to those in aircraft, may be deployed. Once the capsule reaches its destination safely, it would be removed from service. The safety of the onboard air supply will be comparable to that in commercial aviation due to the anticipated implementation of similar technical solutions.

In the event of decompression, all capsules would be brought to an emergency stop, and the pressure inside the tube would be increased along its entire length [1,3,5], which at present appears to be the only feasible approach to ensuring passenger safety with regard to decompression illness and barotrauma. However, the effects of various phenomena—including potential detonation caused by the capsule exceeding the speed of sound—on both the tube and the capsule, under conditions where the tube pressure must be raised to approximately 1000 hPa while the capsule is traveling at around 1200 km/h, remain unknown. Based on the current state of knowledge, it appears that theoretical analyses in this area should be supplemented by experimental verification.

Stations in tubular transport (HYPERLOOP) are intended to be minimalist; however, in practice the boarding process and station layout will be considerably simpler than at airports. Given the short travel times and frequent departures, passenger flow through each station is expected to be continuous, in contrast to the pulse-like traffic at airports, where delays often occur. Safety and security remain the highest priority; therefore, screening procedures will be carried out in a manner similar to airport security checks. Nonetheless, these procedures may be significantly streamlined to minimize waiting time and maintain a more continuous passenger throughput.

The HYPERLOOP system will be capable of transporting passengers between Los Angeles and San Francisco in approximately 35 minutes, meaning that capsule components will be subjected to frequent and substantial pressure fluctuations. This will have a considerable impact on, for instance, copper components, which must be used extensively in the system's construction.

One of the phenomena affecting copper under frequent, large pressure variations is extrusion (Fig. 5) and intrusion (Fig. 6), which occur due to the so-called twinning mechanism (Fig. 7) during plastic deformation of copper single crystals under shear.

This issue has been described by the authors in earlier studies [6,7], and it has a significant influence on insulating materials and on all mechanically sensitive materials in direct contact with copper, as well as on components manufactured from copper or copper-rich composites.

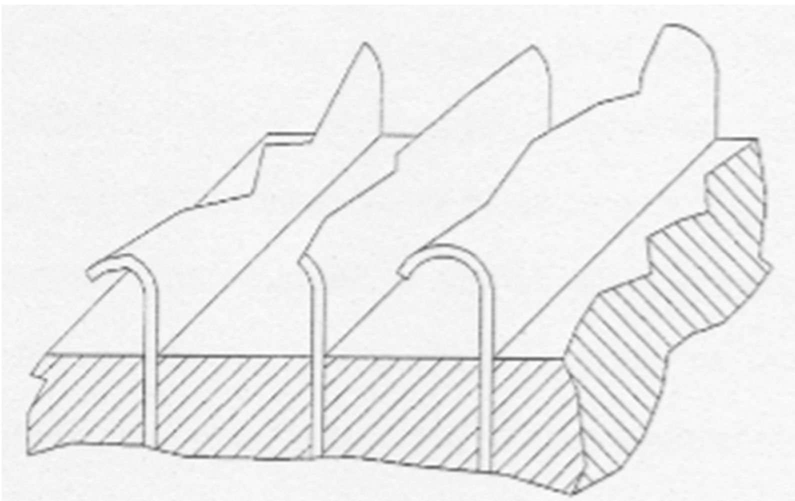

Fig. 5 Schematic representation of extrusion formation [6,7].

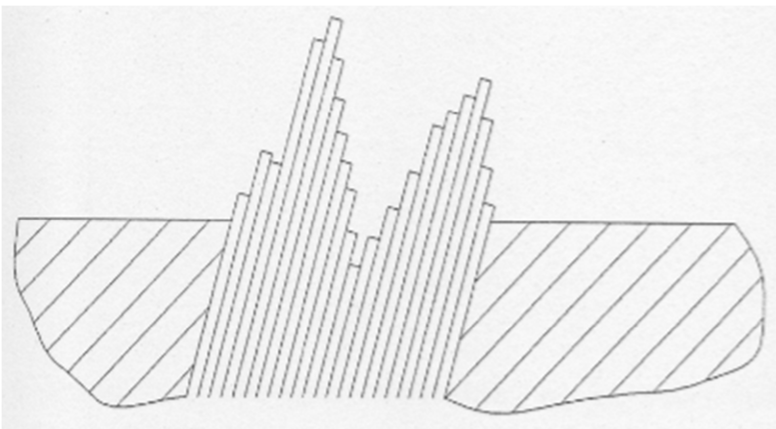

Fig. 6 Schematic representation of intrusion formation [5,6].

The formation of extrusions and intrusions in electrical conductors is induced by frequent and substantial pressure fluctuations, which generate internal stresses within the material and cause rapid variations in bending, tensile, and compressive forces. This necessitates the use of appropriately selected insulating materials as well as individually engineered technical and structural solutions for all equipment, including electrical wiring. The schematic of the plastic deformation mechanism in copper—representing the primary cause of such defects, whose consequences may pose serious hazards—is shown in Fig. 7.

These phenomena often lead to long-term and unpredictable effects; therefore, their causes must be mitigated at all stages of design and operation [6,7].

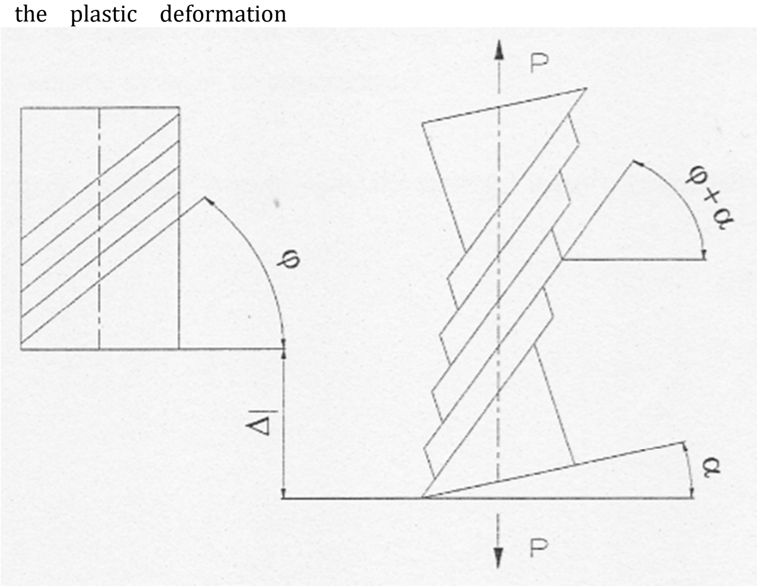

Fig. 7 Schematic of the plastic deformation mechanism of a single crystal under shear [6,7].

Another critical challenge within the capsule is maintaining an appropriate air mixture—not only with respect to oxygen concentration, but, more importantly, purity, specifically the levels of CO_2, CO, and other harmful chemical compounds as well as pathogenic microorganisms. As of today, it appears that this issue may be addressed using advanced membrane-based technological solutions, for example:

- Ultrathin fibers (with diameters of 50–300 nm), forming a porous layer capable of capturing particulates and aerosols, thereby removing PM_{10}, $PM_{2.5}$, PM_1, allergens, and microorganisms with an efficiency of approximately 99%. Such a solution would substantially reduce the risk of infection associated with breathing in a closed environment, although it would not eliminate it entirely [8].
- Hybrid membranes with nanoparticles (NP-membranes), which combine mechanical filtration with active contaminant degradation. Common modifications include:
  - TiO_2 – photocatalytic decomposition of VOCs and bacteria,
  - Ag^+ – antibacterial activity,
  - Graphene or GO – gas adsorption and enhanced conductivity,

  all of which are self-regenerating under UV exposure.
- MOF membranes (metal–organic frameworks) with capabilities for the removal of SO_2, CO_2, NO_2, NO_x, and H_2S.

In comparison, the application of membrane technologies offers the following advantages:

Tab. 2

Comparison of modern membrane technologies [2,8,9].

Technology	Removed contaminants	Advantages	Limitations
Hybrid membranes	VOCs, microbes	self-cleaning, high activity	cost
Nanofibers	PM, bacteria	high filtration efficiency, low resistance	UV degradation
LBM	CO_2, NH_3	high absorption efficiency	more difficult stabilization
MOF	acidic gases, CO_2	high selectivity	moisture sensitivity
Ceramic membranes	PM, NO_x	operation at high temperatures	cost and brittleness
Electrosorption	PM, ions	regeneration capability	requires power supply

According to the authors, this is currently one of the most promising solutions. Other significant risks associated with this issue include, among others:

- the use of oxygen-enriched gas mixtures,
- the occurrence of claustrophobia among passengers,
- terrorist threats,
- natural disasters,
- operational hazards.

As shown, tubular transport functions under technical and medical conditions that differ substantially from those of conventional rail systems, and this diverse set of interdisciplinary issues must be integrated into a coherent framework that ensures safe and efficient transportation.

CONCLUSIONS

The technical and operational solutions in tubular transport are closely interconnected with aspects of medicine and hyperbaric science. Both domains require highly specialized analyses due to the considerably greater variability of technical parameters and the health-related factors that must be taken into account in such a transport system.

It appears that the HYPERLOOP concept was initially developed primarily to obtain patents and new technologies at minimal cost, and that the project itself was originally intended for space-related applications rather than terrestrial use. However, it may ultimately prove effective on Earth, as suggested by emerging analyses of solutions proposed in China and Spain [10], as well as by the growing interest in tubular transport among numerous research institutions.

At present, all research should to a much greater extent incorporate the scientific achievements and practical experience of specialists in hyperbaric medicine, aerospace medicine, and the operation of rail vehicles and aircraft.

The considerable diversity of the issues involved necessitates the use of interdisciplinary, individually tailored solutions when developing systems that must ensure both safety and efficiency of the project.

The considerable diversity of scientific approaches, research methodologies, and the interdisciplinary nature of the problem make it difficult to provide a concise and scientifically rigorous characterization of the issue.

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Andrzej Krzyszkowski
Uniwersytet Radomski im. Kazimierza Pułaskiego
Jacka Malczewskiego 29,
26-600 Radom