NICOLHy - Novel Insulation Concepts for LH_2 Storage Tanks

Project deliverable

D1.2 Preliminary design of novel insulation concepts for LH_2 storage tanks

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The NICOLHy Consortium:

Participant No.	Short name	Country
1 (Coordinator)	BAM	Germany
2	UniBo	Italy
3	DLR	Germany
4	NTNU	Norway
5	NTUA	Greece

Content

Abbreviations:

BAM	Bundesanstalt für Materialforschung und -prüfung
CapEx	Capital expenditure
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EU	European Union
EVOH	Ethylene vinyl alcohol copolymers
He	Helium
HGM	Hollow glass microspheres
JU	Joint Undertaking
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
N_2	Nitrogen
NIC	Novel insulation concept
NTNU	Norwegian University of Science and Technology
NTUA	National Technical University of Athens
O_2	Oxygen
OpEx	Operating expense
PEEK	Polyether ether ketone
PEI	Polyetherimide
PU	Polyurethane
SC	Supports and connections
UniBo	Alma Mater Studiorum - Università Di Bologna
VIP	Vacuum insulation panel
WP	Work package

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1 Introduction

Liquid hydrogen (LH_2) is transported and stored at –253 °C, as it has higher volumetric energy density compared to pressurized hydrogen gas [1]. Due to the large temperature difference to the surrounding environment, thermal insulation is particularly important to minimize hydrogen evaporation, keeping the fuel in the liquid phase. In addition, LH_2 tanks must be cost-effective to manufacture and maintain, be energy-efficient, and inherently safe. The combination of these aspects must also ensure the durability of these storage systems, which are expected to operate for more than 25 years with few and short maintenance intervals.

To date, large LH_2 storage tanks have been designed and built following similar criteria to the small tanks for liquefied natural gas (LNG) [2], [3]. They have a double-wall structure. The space between the inner shell and the outer jacket contains a filling material commonly kept under vacuum conditions. The combination of vacuum and insulating materials impedes heat exchange through radiation, heat conduction, and convection [3], [4]. This structure constitutes a thermal superinsulation. Several layers of foil or powder are commonly used as filling materials. As mentioned, the insulation system's performance tends to increase with decreasing pressure [5]. The shape of these tanks is typically spherical or consists of two hemispheres connected by a cylindrical part. This design enables to handle the pressure from the vacuum on the inner and outer walls, as well as any internal pressure in the tank. Furthermore, the spherical shape has the lowest ratio of surface area to volume among all the geometries, which makes it particularly energy efficient.

Large-scale tanks for LNG cannot be used for the storage of LH_2 since the former is stored at –161 °C and the latter at approximately –253 °C [6]. Large-scale tanks for LNG have capacities ranging from approximately 30,000 to 220,000 m³. They are insulated with materials used in the construction industry, such as aerogels, polyurethane foams, rock wool, or perlite. All these materials are highly porous and contain air in their interstices. Air is a good insulator for LNG. However, it consists primarily of nitrogen and oxygen, which condense and freeze well above the storage temperature of LH_2, thus increasing thermal conductivity, mass, and heat capacity of the thermal insulation. Furthermore, the combination of liquid or frozen oxygen, flammable materials, and small amounts of energy can cause sudden combustion and even explosions, which can be associated with the sudden failure of the thermal insulation. The resulting heat would promote the vaporization of the LH_2 stored within the tank and overpressurize the system, eventually causing a catastrophic loss of containment. Nevertheless, replacing the air in the insulation material with gases with sufficiently low boiling points, such as helium or hydrogen, could lead to significantly higher thermal conductivities [6], making the storage of LH_2 neither economically nor energetically viable .

Along with technical issues associated with air condensation, spherical storage systems have several disadvantages that make them unsuitable for large-scale applications [7]. Although they have the lowest surface area to volume ratio among all the geometries, the significance of this advantage decreases as the size of the system increases. Current systems (with a maximum storage capacity of 4,700 m³ [8]) are significantly smaller than those required to establish a widespread hydrogen economy. In the medium to long term, tanks' capacities of up to 40,000 m³ for ships and 200,000 m³ for stationary storage facilities will be required. For many technical applications, such as a ship, spherical shapes imply less efficient space utilization than cylindrical or rectangular shapes. In fact, the transport capacity can be increased by 65 % by switching from spherical to prismatic tanks.

The production of double-walled spherical tanks is resource-intensive, challenging to plan, and uncertain regarding labor requirements, quality, and costs. For example, constructing a 4700 m^3 tank at the NASA Kennedy Space Center took around three years. This long production time is the result of a sequence of work packages that cannot be parallelized. It would also be difficult to speed up the production time by continuously improving the processes. Due to the size of the tank, a large part of the assembly and manufacturing processes must take place on the construction site. This makes production dependent on the weather, which makes it slower and more expensive than workshop production. Due to the design characteristics, the possibilities for quality assurance during production are limited. Necessary performance evaluations can only be conducted after final integration.

In addition, the time required to produce inner and outer walls can be significantly long, thus delaying the commissioning considerably. This also makes it clear that the entire manufacturing process is subject to significant labor requirements fluctuations. Another disadvantage of spherical storage tanks is that they have a double wall. This means they are not tolerant of multiple inner or outer wall faults. Each of these faults would cause an increase in pressure, leading to a higher heat flow from the environment to the cryogenic fuel.

To overcome the abovementioned limitations, deliverable D1.2 aims to propose new insulation concepts suitable for large-scale liquid hydrogen storage. The proposed concepts are founded on the expertise of the project participants, as well as on the comprehensive literature review conducted within the framework of WP1. The advantages and drawbacks of each LH_2 insulation system are based on the experience gained from large-scale LNG tanks. The utilization of new designs based on VIPs is explored, owing to the promising features of these technical solutions regarding scalability, safety, and costs. The current limitations in terms of materials' performance, weight, size, scalability, vacuum degree, and construction process are attentively analyzed to develop safer and more efficient concepts for stationary and maritime applications. The critical aspects of the novel solutions developed are also highlighted.

2 Methodological approach

The definition of the novel insulation concept is based on the technical requirements specified in the Grant Agreement of the NICOLHy project (Project No. 101137629) [7], which are listed below:

- A boil-off rate of 0.1 mass-% / day should be guaranteed
- The novel insulation should be applicable to stationary tanks with capacities up to 200,000 m^3 and maritime carriers with capacities up to 40,000 m^3
- The storage cost should be less than 20 euros/kg
- The novel insulation concept could be based on vacuum insulation panels
-

Based on the project's requirements, a set of parameters and target characteristics was defined. These include all the desirable features of the novel insulation concepts for large-scale LH_2 tanks. They cover thermal insulation performance, structural integrity, manufacturability, maintainability, durability over time, safety, economic feasibility, and the environmental sustainability of the insulation system. The aim was to perform a holistic preliminary analysis of the most promising concepts to investigate in detail in the future. The requirements are listed in Section 2.1, explaining their significance for the project's targets.

Then, each Consortium partner independently developed at least three novel insulation concepts, highlighting their main technical characteristics, advantages, and limitations. Afterwards, the proposed concepts were thoroughly analyzed, highlighting the advantages and disadvantages, as well as the similarities and differences, and clustering common concepts. Subsequently, the novel insulation concepts were discussed in panels leveraging the expertise of the consortium partners. The discussion ended with the selection of different variants of promising insulation systems. Considering the whole storage system allowed for considering different tank shapes, orientations, single or double-wall concepts, materials' performance, connections, safety devices, construction methodologies, sustainability, and circularity.

Finally, the key features and most promising aspects of various selected concepts were highlighted to obtain the optimal solution for further investigation. Figure *1* schematically illustrates the methodology's flow diagram.

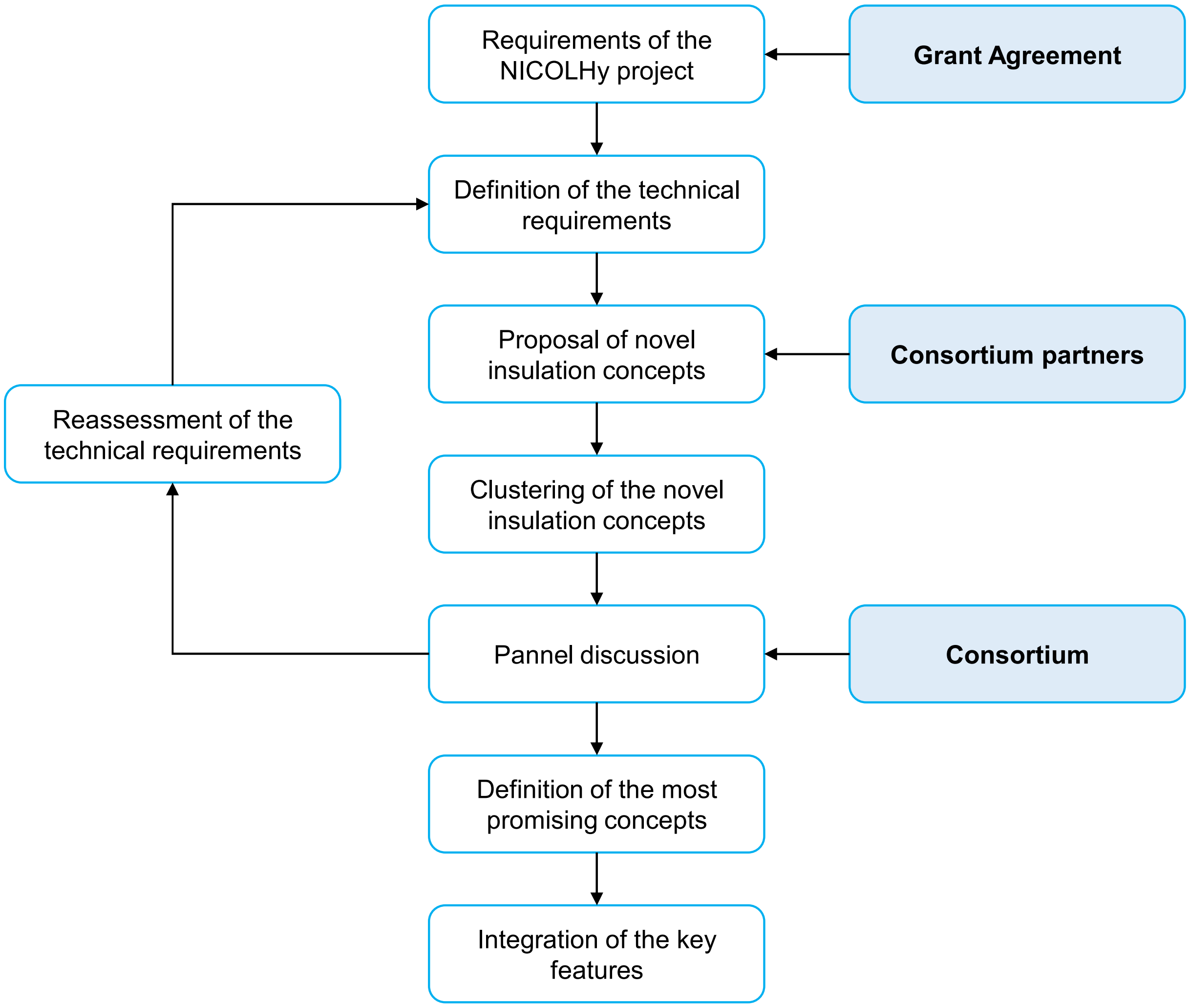

Figure 1: Flow diagram of the methodology adopted for selecting the most promising novel insulation concepts

2.1 Technical requirements

1. **Volume occupation**

LH_2 tanks can have different shapes and designs, particularly for maritime applications, where the storage space is limited. The insulation system should be capable of adapting to a range of potentially complex tank geometries and accommodate design variations in tank shape without compromising the insulation performance.

2. **Boil-off rate**

The primary purpose of the insulation system is to minimize heat transfer between the tank and the surrounding environment. Heat leakages from the environment to the cryogenic storage tank will result in boil-off gas formation, thus determining a net loss of fuel over time. Therefore, the boil-off rate is crucial since it is univocally dependent upon the insulation system's overall heat transfer coefficient, which accounts for conductive, convective, and radiative heat transfer. The presence of thermal bridges should be thoroughly evaluated.

3. Specific heat capacity

The specific heat capacity determines the insulation's ability to absorb and store heat, which impacts loading/unloading cycles and boil-off management. This parameter is crucial for thermal stability during operations (e.g., during tank filling or emptying).

4. Resistance to thermal deformations

The tank will undergo significant temperature changes during filling, storage, and discharge cycles. The insulation system must maintain integrity despite the mechanical stresses induced by thermal expansions and contractions. In addition, it should tolerate the thermal expansion and contraction of the tank's material without degrading its performance.

5. Load bearing capability

The insulation system must support external loads (e.g., mechanical stress from the tank structure, external pressure, and its own weight) without compromising thermophysical properties and structural integrity. In addition, it must withstand the mechanical stresses imposed during transportation, installation, and operation, especially in the case of mobile applications.

6. Parallel manufacturability

Producing and installing the insulation materials on a large scale in a short time is crucial. The ability for parallelization in the manufacturing and the integration processes can support this requirement while maintaining and increasing the quality . Cost-effectiveness and construction time depend on the ability to manufacture insulation at scale using efficient processes.

7. Pre-manufacturability and quality control

The insulation should be pre-manufactured or prefabricated in an industrial environment where it is possible to monitor, verify, and ensure that its performance meets the technical requirements indicated by the standards. In addition, pre-manufacturing insulation components can speed up tank assembly, reduce onsite labor, and improve consistency in quality. Quality control methods should be clearly defined to ensure compliance with the required quality standards.

8. Maintainability

Ease of maintenance affects the tank's long-term viability. If the insulation degrades over time or is damaged, it should be easy to repair without excessively affecting the tank's operations. Inspection, maintenance, repair, and replacement procedures should be simple, economical, and safe. Condition-based maintenance approaches should be possible.

9. Durability

The insulation system should retain its properties over time, even in harsh environmental conditions (extremely cold temperatures, moisture, stress cycles, vibrations, marine environments, etc.). Material durability consists of three primary factors: chemical durability, mechanical durability, and ability to withstand the environmental degradation. Therefore, the maximum value of material durability corresponds to the material with the best overall performance. Durability is essential for reducing the frequency and cost of repairs and replacements, guaranteeing the tank's economic feasibility over its lifetime.

10. Fire resistance

Fire resistance is critical for safety, particularly in high-risk environments where leaks or accidents may cause fires or explosions. Resistance to ignition and the ability to withstand high temperatures or flames without losing its loadbearing capacity, integrity, and thermal insulation properties is crucial. Smoke emission during a fire is another critical factor that needs to be considered. The presence of toxic gases during fire incidents poses a severe risk to the environment and human healththat should be prevented or minimized.

11. Air condensation avoidance

Air condensation on the tank wall can present a safety issue since it can form an oxygen-rich environment and increase the risk of fires and explosions in the case of unintended release of LH_2 in the surrounding environments. In addition, the air freezing within the insulation system could affect the thermal properties of the insulation system and increase the boil-off rate. It is crucial to minimize the air condensation to ensure that the insulation is not compromised and to prevent the escalation of incidents due to oxygen-enriched atmospheres.

12. CapEx

CapEx is essential for project feasibility, and insulation costs must be balanced against the potential performance and durability over the tank's lifetime. It accounts for all the non-recurring costs for production, installation, and deployment and is expected to significantly impact the feasibility and widespread rollout of the proposed insulation concepts.

13. OpEx

OpEx is an vital factor for project feasibility. It indicates the recurring cost, which can either be fixed, i.e., not changing with production output, or variable, i.e., directly tied to production volume. OpEx accounts for the system's costs during operation, maintenance, loading and unloading, etc. This parameter is expected to be low, considering the nature of a storage system.

14. Environmental impact

With the growing emphasis on sustainability, choosing recyclable insulation materials derived from broadly available sources or contributing to reducing the tank's overall carbon footprint is a crucial factor. Environmental impact quantifies the negative effects of resource production, consumption, and disposal on the environment and human health.

15. Recyclability

Waste production is part of the environmental impact of producing and disposing of insulation systems. To reduce waste, it is recommended to use recyclable materials and design a plan for reusing or recycling components at the end of their life.

3 Proposal of novel insulation concepts

This section compiles all the proposed novel insulation concepts for large-scale LH_2 tanks. Each idea is presented with schematic sketches, a brief description, and a discussion of its expected advantages and limitations. The purpose of these concepts is to serve as a foundation for future discussions and analyses; they are not intended to include comprehensive technical, economic, or environmental evaluations. Following this overview, more detailed analyses will be conducted on a select few promising insulation concepts.

3.1 Novel insulation concept NIC_01

Insulation concept name:	Structural frame
Concept ID:	NIC_01
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.1.1 Sketch

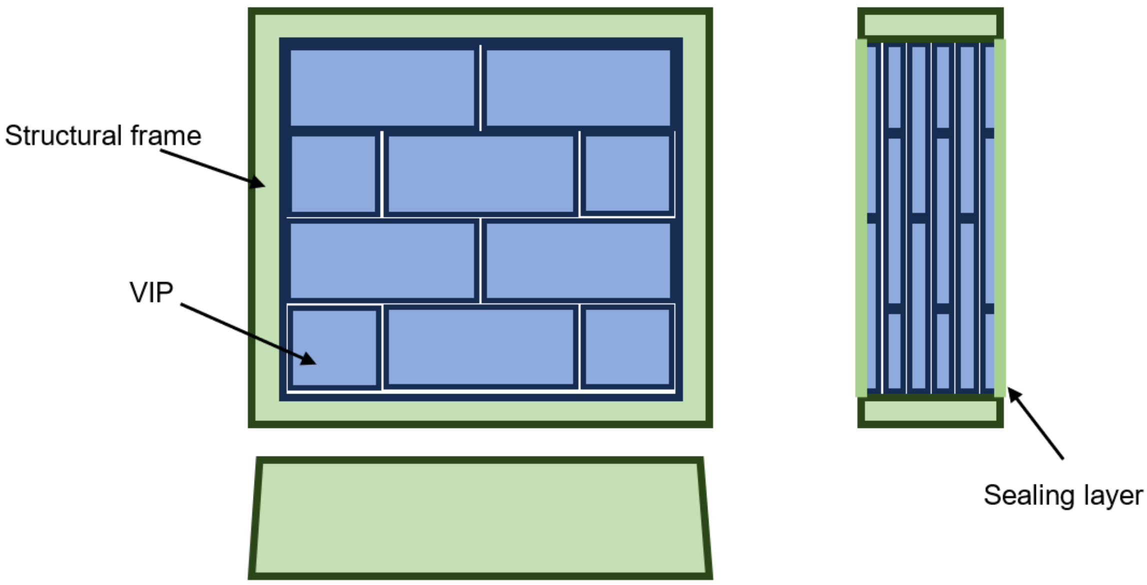

Figure 2: Front, top, and side views of the novel insulation concept NIC_01

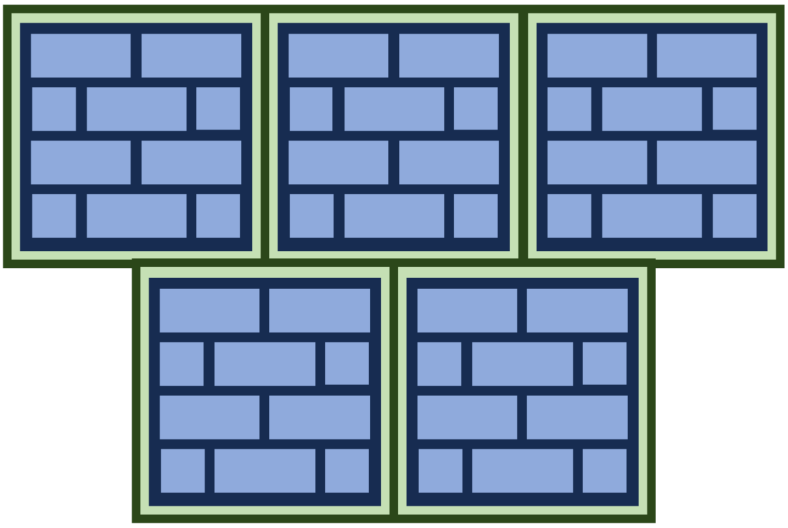

Figure 3: Assembly of the novel insulation concept NIC_01

3.1.2 Description

This concept is based on structural frames that hold a stack of vacuum insulation panels. Each structural frame is constructed from a composite fiber material as reinforcement and a concrete or plastic matrix. The structural frame is exposed to cold and warm conditions and must handle thermal stresses and/or deformations. This could be compensated by bearings in all relevant walls, materials with low thermal expansion coefficient, and a change of size of VIPs could be necessary (depending on their distance from the cold inner wall). The frames with VIPs inside can be sealed and filled with hydrogen or helium gas to prevent liquid oxygen accumulation. The shape of the frame can be trapezoidal or sections of a ring to fit cylindrical tanks. Frames with panels are pre-manufactured and filled with VIPs in industrial environments. The assembly on-site consists of stacking the frames around the inner tank wall. Frames can be connected by a fill material that should be the same as the matrix material of the frame. The manufacturing of the entire storage system lies in building the inner wall of the LH_2 tank and insulating the wall by stacking the structural frames filled with VIPs.

3.1.3 Advantages

- It enables the construction of individual frames
- Medium insulation performance based on direct heat bridges (corresponding to the connections between different structural frames) and medium size of the VIPs
- Medium material effort and a minimum of three different materials (material for the VIPs, composite material for the structural frames, material for the sealing layer)
- The frames build the external gas-tight enclosure
- Decoupling of the load-bearing wall and the insulation within the frames
- Mechanical loads on VIPs are limited since the frame should carry the weight of the insulation system
- VIPs can move to deal with thermo-mechanical stresses
- Roof of the tank can be supported by the secondary wall of the tank
- VIPs are mounted within the module, therefore they do not need to be connected or held in any other way

- Very good pre-manufacturing potential
- Good to parallelize the tank manufacturing
- Very good quality control
- Highly redundant
- In case of maintenance full modules can be replaced and repaired without compromising the rest of the insulation system

3.1.4 Disadvantages

- The load-bearing wall consisting of several frames must deal with thermal deformations
- There are several thermal bridges that increase the overall wall thickness
- It is possible that polymeric materials are put into contact with liquid oxygen

3.2 Novel insulation concept NIC_02

Insulation concept name:	Wall studs inner
Concept ID:	NIC_02
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.2.1 Sketch

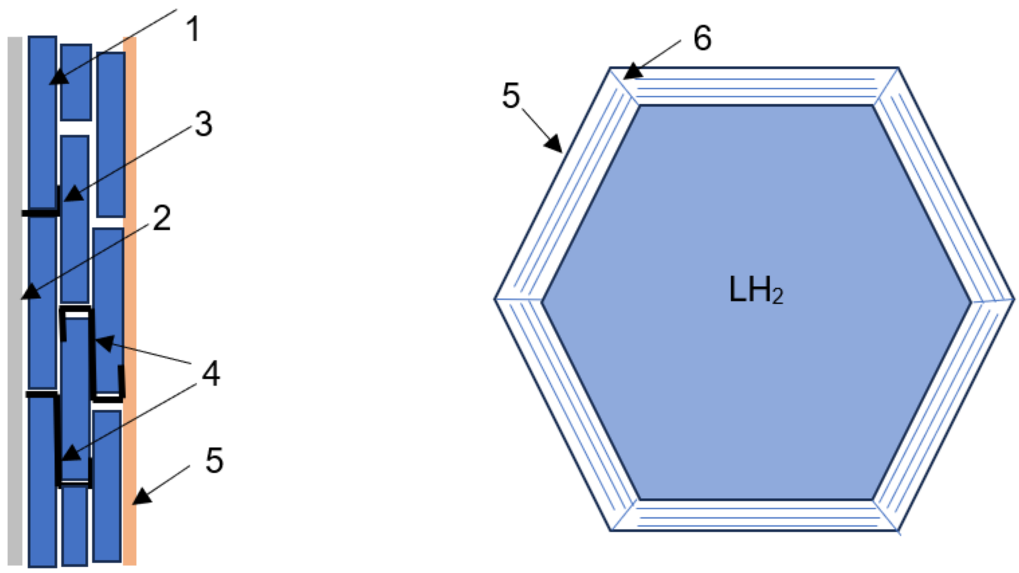

Figure 4: Side and upper views of the novel insulation concept NIC_02

3.2.2 Description

Studs **(3)** are mounted by welding or glueing on the inner tank wall **(2)**. These components can be made of metal, plastic composite, or a combination of the two. The VIPs **(1)** are mounted on the studs. To enable thermal displacements, the VIP's size must decrease from the inner layers to the outer layers. Studs could be designed to only hold the innermost layers; the panels further outside are mounted to those with additional mounting hardware **(4)**. Studs can hold the panels by their shape and gravity as if they are placed on a shelf or by creating friction between panels, or between panels and tank wall (as in a bolted connection). A gas tight barrier **(5)** can be added to prevent air ingress. Additionally, the overall insulation system could be separated into smaller sections by a thin foil **(6)** to facilitate the inspection and maintenance operations.

3.2.3 Advantages

- It is based on the fundamental idea of applying VIPs for LH_2 storage tanks and is also close to the solution applied in LNG tanks (it is a simple concept based on experiences from the LNG industry)
- Enables the construction of cubes. Prismatic tanks must deal with special elements or come along with side-by-side constructions that could limit the presence of thermal bridges. This could also be an opportunity to cluster the overall insulation system in sections that are separated by thin foils
- It is possible to build very large VIPs (13.6 × 3 m²) and install them from the top through a crane
- Good insulation performance
- Low material effort and a minimum of two different materials (VIPs and metallic or composite material for the studs)
- External gas-tight enclosure could be necessary
- Requires a load-bearing construction next to the insulation (on the inner wall and/or secondary wall)
- Roof of the tank can be supported by the inner wall of the tank
- Thermal deformations are handled by the VIPs and are relatively limited
- The structure is not subjected to thermal deformations
- VIPs can be handled in service from the warm side
- Good pre-manufacturing potential
- It is easy to parallelize the tank manufacturing
- Very good quality control
- Highly redundant

3.2.4 Disadvantages

- The design of the VIPs must deal with thermal shrinking; therefore, the outermost layers must be smaller than the inner ones
- Inspecting and maintaining is difficult but it might not be necessary within the lifetime of the storage system

3.3 Novel insulation concept NIC_03

Insulation concept name:	Wall studs outer
Concept ID:	NIC_03
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.3.1 Sketch

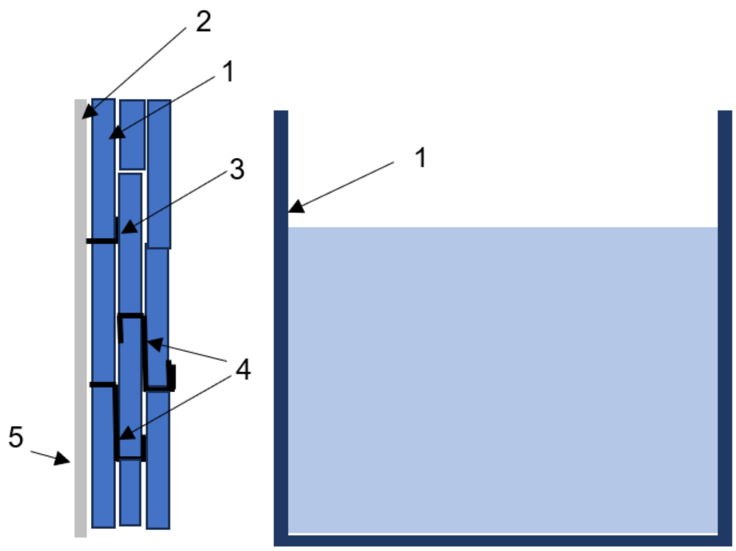

Figure 5: Side view of the novel insulation concept NIC_03 and cross-section of the tank

3.3.2 Description

LH_2 is stored in a large-scale vertical cylinder **(1)** like those used for LNG. Unlike the previous concept, the outer tank **(2)** is bearing the insulation system. Studs **(3)** are mounted by welding or glueing on the outer (warm side). These components can be made of metal, plastic composite, or a combination of the two. The VIPs **(1)** are mounted on the studs, which are designed to hold only one layer of VIPs. Studs can hold the panels by their shape and gravity as if they are placed on a shelf or by creating friction between panels, or between panels and tank wall (as in a bolted connection). A gas tight barrier **(5)** can be added to prevent air ingress.

3.3.3 Advantages

- It is based on the fundamental idea of applying VIPs for LH_2 storage tanks and is also close to the solution applied in LNG tanks (it is a simple concept based on experiences from the LNG industry)
- Enables the construction of cubes. Prismatic tanks must deal with special elements or come along with side-by-side constructions that could limit the presence of thermal bridges. This could also be an opportunity to cluster the overall insulation system in sections that are separated by thin foils
- It is possible to build very large VIPs (13.6 × 3 m²) and install them from the top through a crane
- Good insulation performance

- Low material effort and a minimum of two different materials (material for the VIPs and metallic or composite material for the studs)
- External gas-tight enclosure could be necessary
- Requires a load-bearing construction next to the insulation (on the outer wall and/or secondary wall)
- Roof of the tank can be supported by the outer wall of the tank
- Thermal deformations are handled by the VIPs and are relatively limited
- The structure is not subjected to thermal deformations
- Good pre-manufacturing potential
- It is easy to parallelize the tank manufacturing
- Very good quality control
- Highly redundant

3.3.4 Disadvantages

- Inspecting and maintaining is difficult but it might not be necessary within the lifetime of the storage system
- In case of a failure a single VIP, it cannot be removed
- There is a larger view factor between the single VIP layers compared to the NIC_02 concept, that result in slightly lower thermal performance
- VIPs can only be handled in service from the cold side

3.4 Novel insulation concept NIC_04

Insulation concept name:	Clustered inner wall
Concept ID:	NIC_04
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.4.1 Sketch

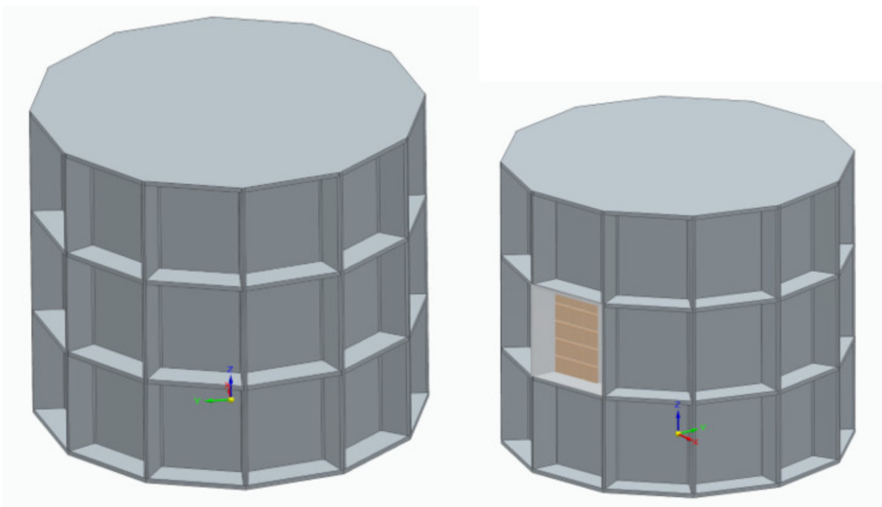

Figure 6: View of the LH_2 storage tank for the novel insulation concept NIC_04

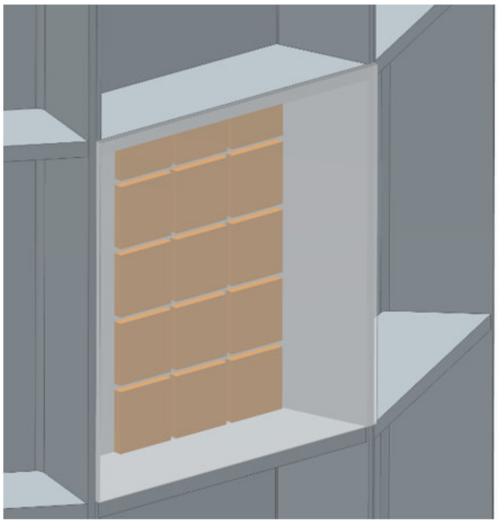

Figure 7: Magnification of a single module of the novel insulation concept NIC_04

3.4.2 Description

The inner tank is built with large outside structure composed of clustered chambers. The VIPs are placed within the chambers. Any chamber can be sealed to the outside.

3.4.3 Advantages

- Enables the construction of individual forms
- Medium insulation performance due to the direct heat bridges from the environment to the LH_2 tank and the medium size of the VIPs
- Medium material effort and a minimum of two different materials (material for the VIPs and metallic material for the chambers)
- There is an external gas-tight enclosure in each chamber
- The load-bearing wall and the insulation within the chambers are decoupled
- Roof of the tank can be supported by the secondary wall of the tank
- VIPs are mounted within the module, therefore they do not need to be connected or held in any other way
- Medium-good pre-manufacturing potential
- Good quality control
- Highly redundant
- In case of a degraded performance, a single chamber can be opened, inspected, and maintained

3.4.4 Disadvantages

- Structure directly attached to tank wall provides thermal bridge
- Frames made from steel must handle thermal stresses and deformations; considering the large size of the storage system, the thermal deformation could be significant

3.5 Novel insulation concept NIC_05

Insulation concept name:	Huge panels
Concept ID:	NIC_05
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.5.1 Sketch

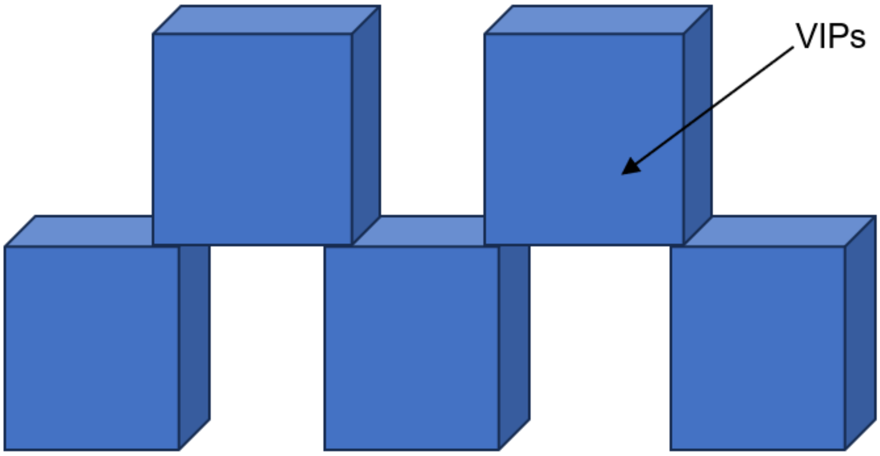

Figure 8: First layer of VIP of the novel insulation concept NIC_05

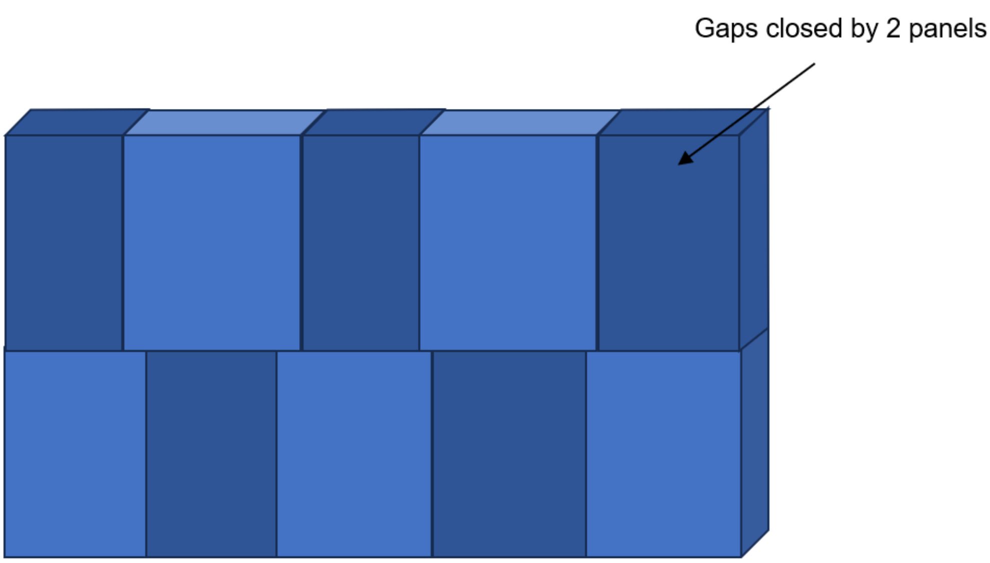

Figure 9: Second layer of panels of the novel insulation concept NIC_05

3.5.2 Description

Very large (3 × 12 × 0.5 m^3) panels are pre-fabricated in a factory and placed around the tank wall on site leaving a “gap”. The gap is closed on-side by panels, filled with core material, and evacuated, creating a “VIP” on site. In this insulation system, any VIP and panel must deal with thermal deformations, that can be compensated by beadings in all relevant walls without changing the external shape.

3.5.3 Advantages

- Enables the construction of individual forms
- Medium number of insulations elements that needs to be handled
- Good to medium insulation performance based on the limited number of direct heat bridges due to the large size of the VIPs and the low number of intermediate walls
- Low material effort and two different materials (material for the VIPs and metallic material for the chambers)
- No gaps between panels by design
- The combination of VIPs and panels build the gas-tight enclosure
- The insulation could be also the load bearing wall
- The roof of the tank can be supported by the secondary wall of the stationary tank
- Medium pre-manufacturing potential
- Good quality control
- Good redundancy
- Very good to parallelize the tank manufacturing
- In the case of a malfunctioning, the inspection and maintenance can be arranged from the warm side

3.5.4 Disadvantages

- Parts of the insulation must be partly built on-site
- Lower redundancy compared to the initial VIP concept
- Requires insulation manufacturing on-site (welding, vacuum, and quality assurance)

3.6 Novel insulation concept NIC_06

Insulation concept name:	Huge panels 2
Concept ID:	NIC_06
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.6.1 Sketch

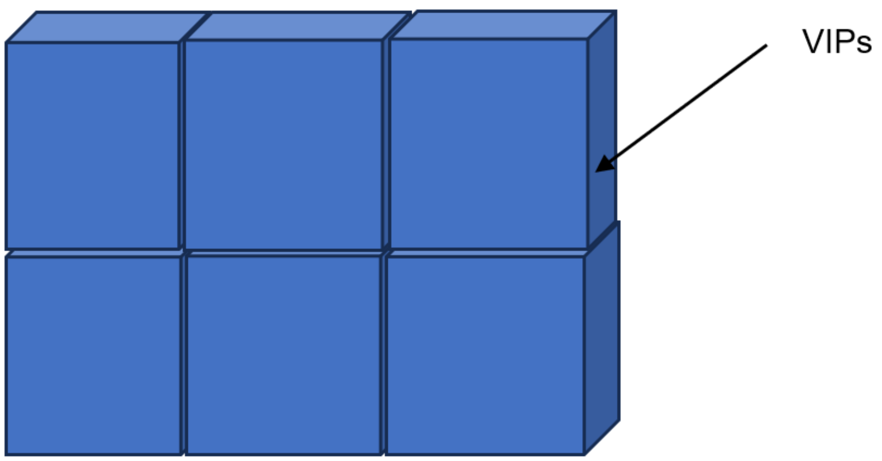

Figure 10: Assembly of the novel insulation concept NIC_06

3.6.2 Description

Very large (3 × 12 × 0.5 m^3) panels are pre-fabricated in a factory, and placed around tank wall on-site. This system needs a gasket between the VIPs or a gas-tight enclosure. In this insulation system, any VIP and panel must deal with thermal deformations, that can be compensated by beadings in all relevant walls without changing the external shape.

3.6.3 Advantages

- Enables the construction of individual forms
- Medium number of insulation elements that needs to be handled
- Medium insulation performance based on the limited number of direct heat bridges due to the large size of the VIPs, double number of intermediate walls compared to the concept NIC_05
- Medium material effort and three different materials
- The insulation could be also the load bearing wall
- The roof of the tank can be supported by the secondary wall of the stationary tank
- High pre-manufacturing potential
- Very good quality control
- Good redundancy
- Very good to parallelize the tank manufacturing
- In the case of a malfunctioning, the inspection and maintenance can be arranged from the warm side

3.6.4 Disadvantages

- Lower insulation performance compared to the concept NIC_05
- It needs a gasket or a gas-tight enclosure
- Lower redundancy compared to the initial VIP concept

3.7 Novel insulation concept NIC_07

Insulation concept name:	Wall with self-mounting VIPs
Concept ID:	NIC_07
Main insulation material:	Vacuum insulation panels
Secondary insulation material:	-

3.7.1 Sketch

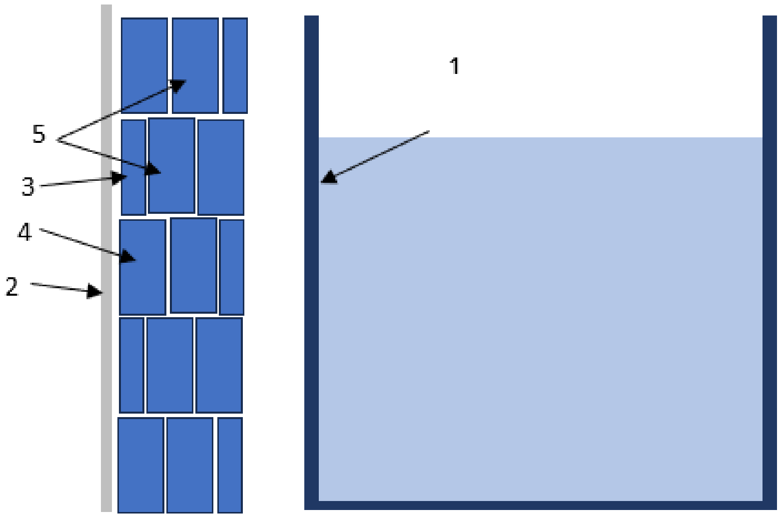

Figure 11: Assembly of the novel insulation concept NIC_07

3.7.2 Description

LH_2 will be stored in a flat-bottomed cylindrical tank (1) like those used for LNG. The outer side of the tank (2) is connected to the VIP layers, which has also a gas-tight barrier to prevent air ingress. VIPs alternate between half (3) and standard thickness (4) along the height of the tank. The VIPs lie on each other (5) like steps in a stair so that the layers on the external side carry the weight of the inner ones, and the thermal deformations accumulate above the VIP's stair. The concept does not allow misalignment by the VIP surfaces in the vertical direction but only in the horizontal.

3.7.3 Advantages

- This solution is similar to what is currently applied to LNG tanks (simple concepts with experience from the LNG industry)
- Enables the construction of modules. For prismatic tanks, edges must deal with special elements or come along with side-by-side constructions that could represent thermal bridges
- Very large VIPs are possible (13.6 × 3 m²)
- VIPs can be installed from the top by a crane
- Good insulation performance
- Low material effort and two different materials
- External gas-tight enclosure could be necessary
- Requires a load-bearing construction next to the insulation (inner wall and/or secondary wall)
- The outer wall supports the tank roof
- Mounting of VIPs is organized by the VIPs themselves
- Thermal deformations are simple to handle and are not connected to the structure
- Good pre-manufacturing potential
- Good to parallelize the tank manufacturing
- Excellent quality control
- Highly redundant

3.7.4 Disadvantages

- Service and maintenance are complex, but the question is if it is necessary during the expected lifetime of the tank
- In case of failure, VIPs cannot be removed
- There is a higher view factor between the single VIP layers, which results in a slightly decreased performance compared to the versions NIC_02 and NIC_03
- Decreased performance compared to the version NIC_03 due to the misalignment only in one direction
- VIPs can only be handled from the cold side during operations

3.8 Novel insulation concept NIC_08

Insulation concept name:	Vacuum insulation panels and polyurethane foam in rigid frame
Concept ID:	NIC_08
Main insulation system:	Vacuum insulation panels filled with perlite
Secondary insulation system:	Polyurethane foam

3.8.1 Sketch

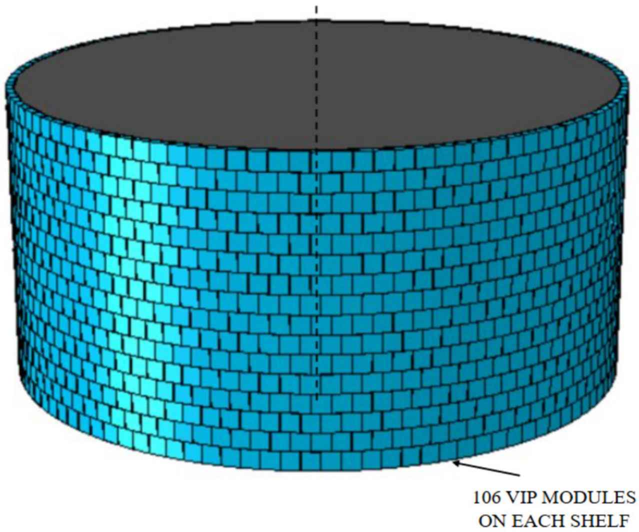

Figure 12: Arrangement of the NIC_08 insulation modules on the outer surface of a cylindrical flat-bottomed tank

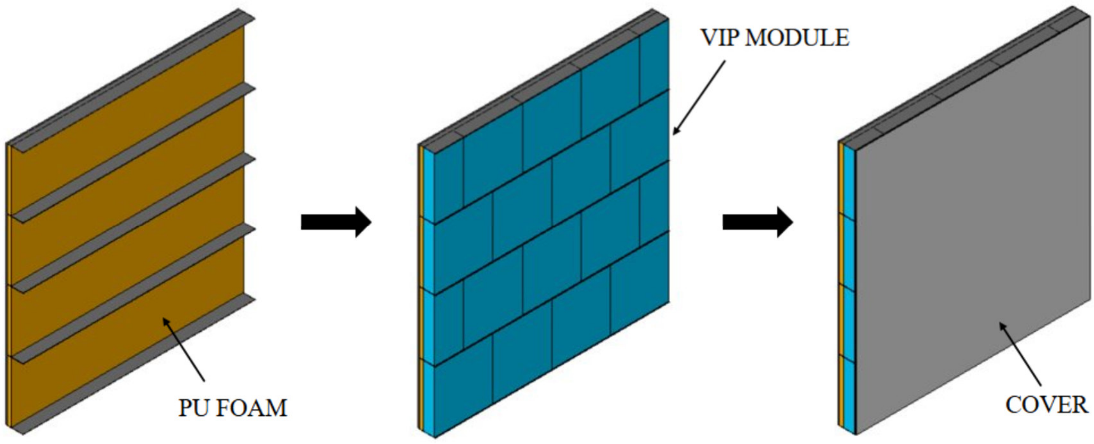

Figure 13: Assembly of the insulation system with polymer foam layer, vacuum insulation panels, and protective cover (NIC_08)

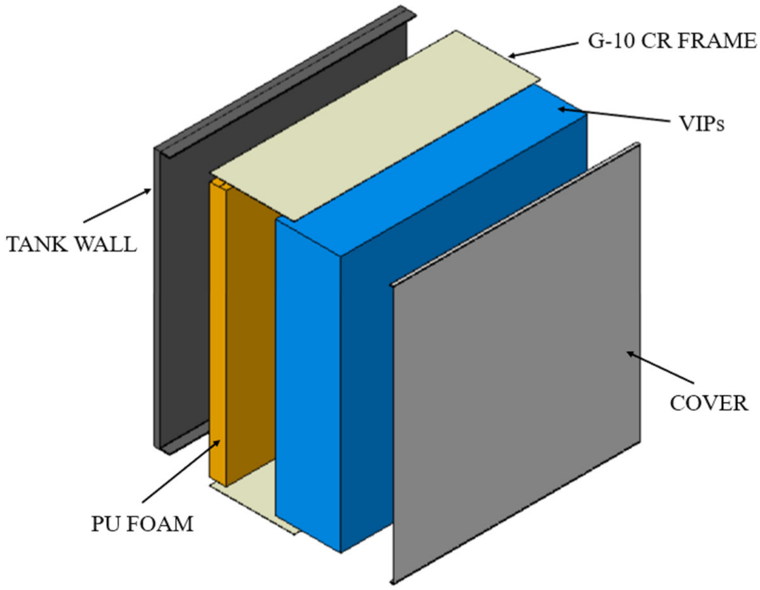

Figure 14: Exploded view of the novel insulation concept NIC_08, indicating the different structural materials and their assembly

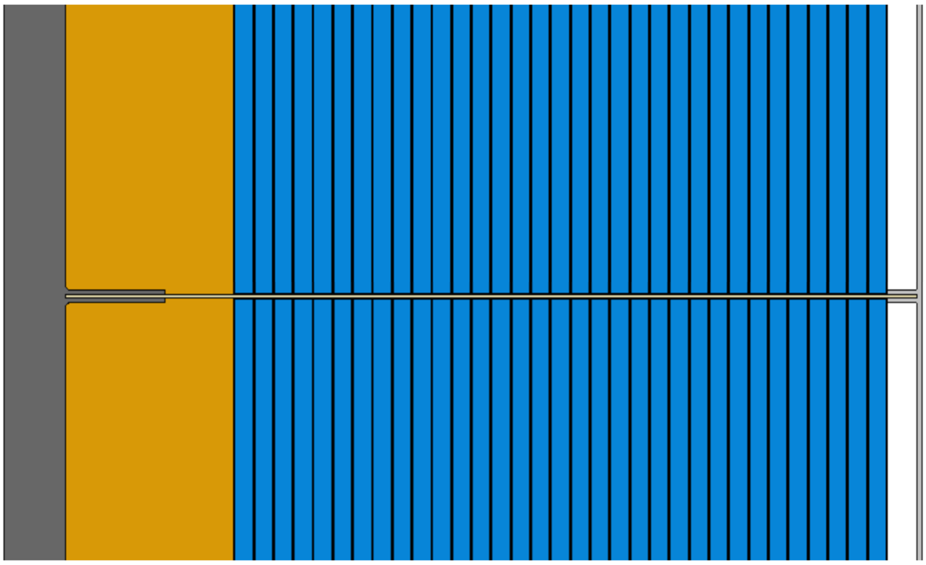

Figure 15: Cross-section of the insulation system of NIC_08 (PU foam is yellow-colored, VIPs are blue-colored, austenitic steel is grey-colored, and fiberglass epoxy is white-colored)

3.8.2 Description

The novel insulation concept NIC_08 for LH_2 storage tanks integrates PU foam and VIPs. The former material consists of a rigid polymer matrix with gas-filled cells, which exhibits excellent dimensional stability at cryogenic temperatures and is cost-effective and easy to apply on irregular surfaces. VIPs comprise a rigid, highly porous core material encased in a gas-tight envelope, evacuated, and sealed. Getters are added to absorb residual gases or vapor within the envelope. VIPs can minimize conductive, convective, and radiative heat transfer, depending on the core and envelope materials and the vacuum conditions.

A rigid frame made of fiberglass epoxy G-10 CR is connected to the tank wall through a groove joint and provides structural support for the insulation system. PU foam constitutes the insulation layer in contact with the tank wall. During normal operations, the tank is approximately at the same temperature of LH_2 (i.e., –253 °C). Hence, the foam layer should be sufficiently thick to avoid oxygen condensation, reaching temperatures higher than –183 °C on the "hot" side. Several VIP layers are placed above the foam and sustained by the rigid frame. The core is made of evacuated perlite, while 5038 aluminum alloy and Teflon are used for the envelope. Notably, the envelope materials do not comply with the requirements for LH_2 service and, therefore, are not exposed to temperatures as low as –253 °C or hydrogen-rich environments. The small space between two VIPs represents a thermal bridge. To address this issue, two subsequent layers of VIPSs are staggered. With this simple arrangement, the second layer compensates for the local lack of insulation of the first layer (and vice versa). A removable metallic cover is placed above the last VIP layer to protect the insulation system from exposure to atmospheric agents and impact with external objects. The cover is attached to the rigid frame and painted with a reflective coating. Therefore, each module includes the PU foam, several staggered layers of VIPs, and the protective cover, all positioned between two shelves of the rigid frame, as shown in Figure 14 and Figure 15.

3.8.3 Advantages

- Low heat transfer regardless of the thermal bridges due to the rigid frame; higher insulation performance can be obtained by adding more VIP layers
- The structural materials have good resistance to thermal deformations even with significant temperature changes
- The system has excellent load-bearing capability; the rigid frame sustains the weight of the entire insulation system as well as external loads
- It is a modular structure that is potentially scalable to very large sizes
- The production of the VIPs can be parallelized
- The VIPs can be produced in an industrial environment, allowing consistent quality control
- The design is effective in preventing air condensation thanks to the PU foam layer; only a small amount of moisture can form over time
- The system is easy to maintain; damaged modules can be replaced without compromising the entire insulation system
- Moderate operating costs due to reduced boil-off losses, occasional maintenance, reduced energy consumption

3.8.4 Disadvantages

- Can adapt to standard tank shapes but not complex ones due to the rigid frame
- The PU foam can be degraded over time, and the vacuum conditions within the VIPs can be compromised due to air and moisture ingress
- The insulation performance is significantly and rapidly degraded when the system is exposed to fire; it might also release polluting substances when burned
- The capital expenditure depends on the unitary cost of the VIPs that need to be designed for cryogenic applications
- Limited recyclability (mainly due to the envelopes of the VIPs).

3.9 Novel insulation concept NIC_09

Insulation concept name:	Hollow glass microspheres in double-walled modular frame
Concept ID:	NIC_09
Main insulation system:	Hollow glass microspheres
Secondary insulation system:	Polyurethane foam

3.9.1 Sketch

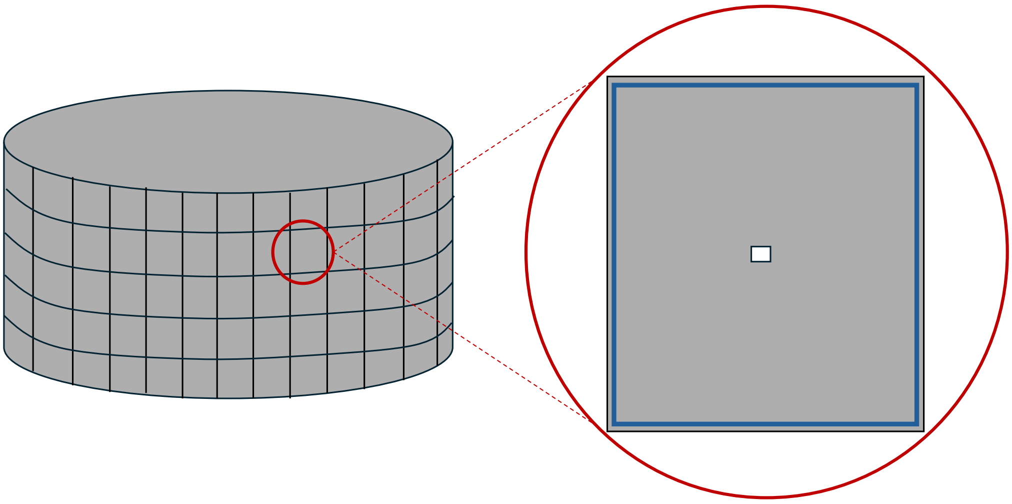

Figure 16: Arrangement of the NIC_09 insulation modules on the outer surface of a cylindrical flat-bottomed tank

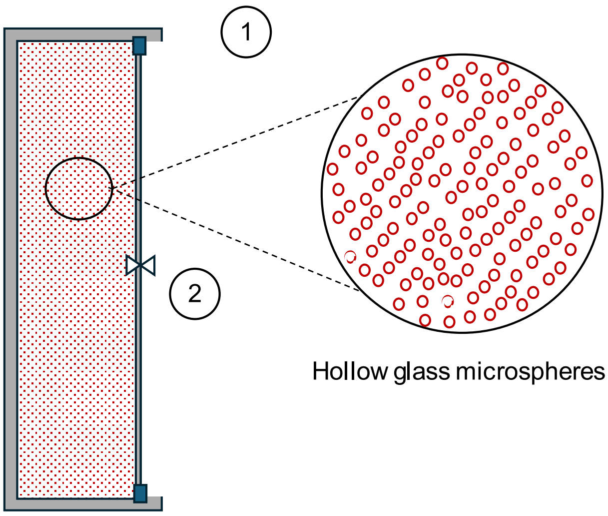

Figure 17: Cross-section of a module filled with hollow glass microspheres under high-vacuum (NIC 09)

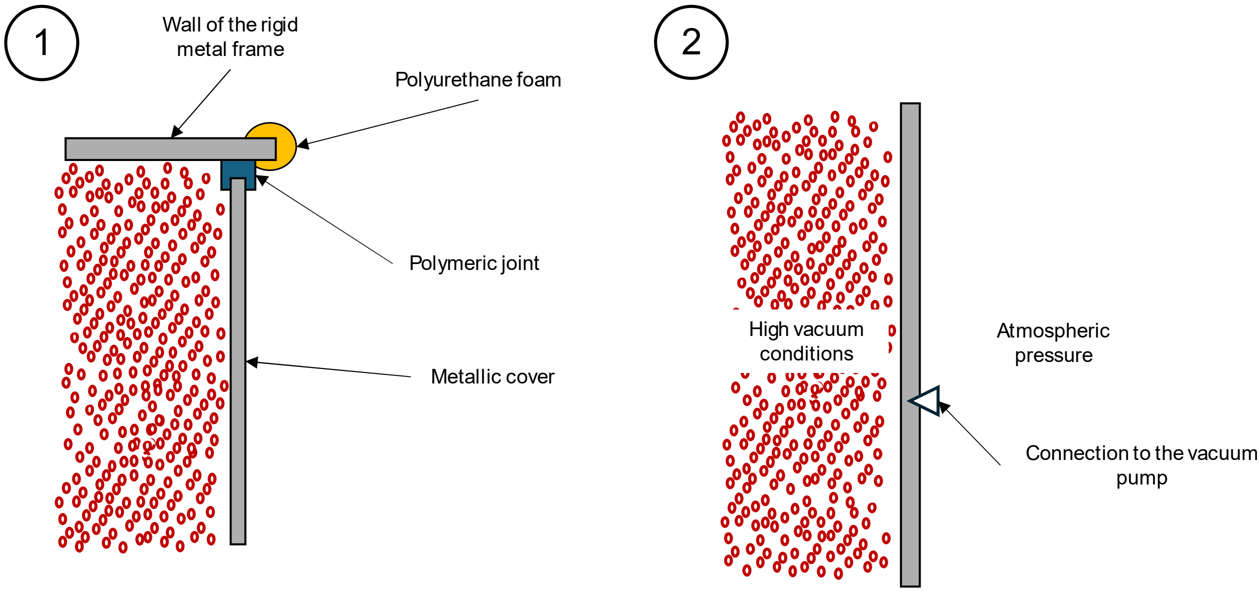

Figure 18: (1) Schematic of the connection between rigid metal frame and cover and (2) schematic of the connection between insulation module and vacuum pump (NIC 09)

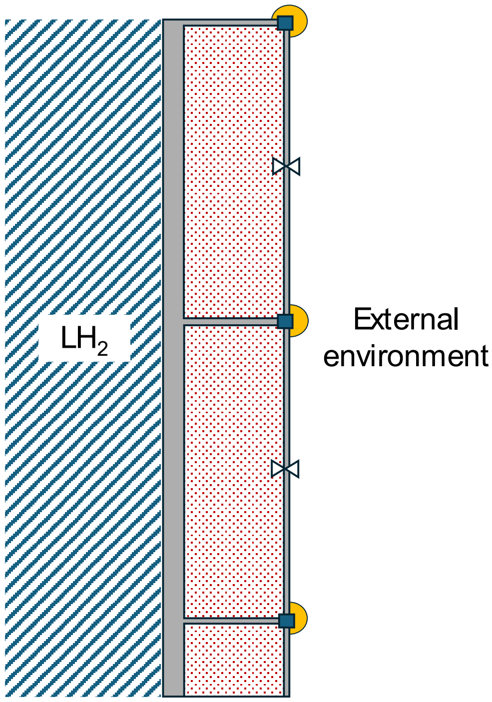

Figure 19: Cross-section of the insulation system NIC_09 (PU foam is yellow-colored, HGMs are red-colored, austenitic steel is grey-colored, and polymeric junctions are blue-colored)

3.9.2 Description

The NIC_09 insulation concept is based on a modular structure that can be adapted to large-scale storage systems and multiple tank shapes. The internal wall of the tank is welded with a rigid metal frame and a honeycomb structure, as shown in Figure 16. The single rectangular cells constitute the modules of the insulation system. Each module is filled with hollow glass microspheres, and a cover is placed on each cell of the honeycomb structure. This is schematically illustrated in Figure 17.

The connection between the cover and the rigid metal frame is crucial for limiting the heat transfer along the thermal bridge. The connection is shown in greater detail in Figure 18 (1). A polymeric material with low thermal conductivity should be used. On the one hand, this connection is exposed to an extreme thermal gradient. In fact, the metal frame is in thermal equilibrium with the inner shell of the tank (i.e., approximately –253 °C) while the cover is at room temperature. On the other hand, it should avoid air access from the environment into the cell (at significantly lower pressure). As a result, the material should be ductile at extremely low temperatures and resistant to humidity (moisture formation is unavoidable).

Finally, the metal cover of each cell is equipped with a valve for connecting a vacuum pump and creating high-vacuum conditions in each module, as shown in Figure 18 (2). The insulation system's performance (i.e., the vacuum conditions in each module) can be monitored continuously through simple pressure sensors. Ordinary maintenance can be potentially conducted only where needed, without emptying the tank or compromising the performance of the entire system.

3.9.3 Advantages

- The modular structure is potentially scalable to very large sizes
- Medium-high insulation performance based on the hollow glass microspheres under high-vacuum conditions and the limited thermal bridges (insulated through polyurethane foam)
- Low specific heat capacity, reducing boil-off during loading operations
- The system has excellent load-bearing capability; the rigid frame sustains the weight of the entire insulation system as well as external loads
- The structural materials have good resistance to thermal deformations even with significant temperature changes
- It is a modular structure that is potentially scalable to very large sizes
- It is easier to create high-vacuum conditions within the single modules than within the whole volume between inner and outer walls
- It is possible to monitor the insulation performance by measuring the vacuum degree of the single modules and allow for condition-based maintenance
- The degradation of a single module does not substantially impact the overall performance of the system
- Good fire resistance of the hollow glass microspheres, no toxic emissions when burned
- Hollow glass microspheres can be recycled, producing low waste

3.9.4 Disadvantages

- Can adapt to standard tank shapes but not spherical ones due to the rigid frame
- Limited parallel manufacturing potential; the vacuum in each module must be created on-site
- There is no redundancy; in the case of failure of a single module, the tank is uninsulated
- The design allows air to condensate and freeze on the PU foam; the thermal performance might be compromised

- The connections between separators and the outer wall are exposed to deformation and stresses caused by the extreme thermal gradients, thus compromising their durability
- The capital expenditure is significantly higher compared to conventional LH_2 storage systems due to the cost of hollow glass microspheres
- The low durability of the system can increase the operating costs due to maintenance and replacement of degraded modules

3.10 Novel insulation concept NIC_10

Insulation concept name:	Modular vacuum insulation panels with hollow glass microspheres
Concept ID:	NIC_10
Main insulation system:	Vacuum insulation panels filled with hollow glass microspheres
Secondary insulation system:	Polybenzimidazole (PBI), Polytetrafluoroethylene (PTFE)

3.10.1 Sketch

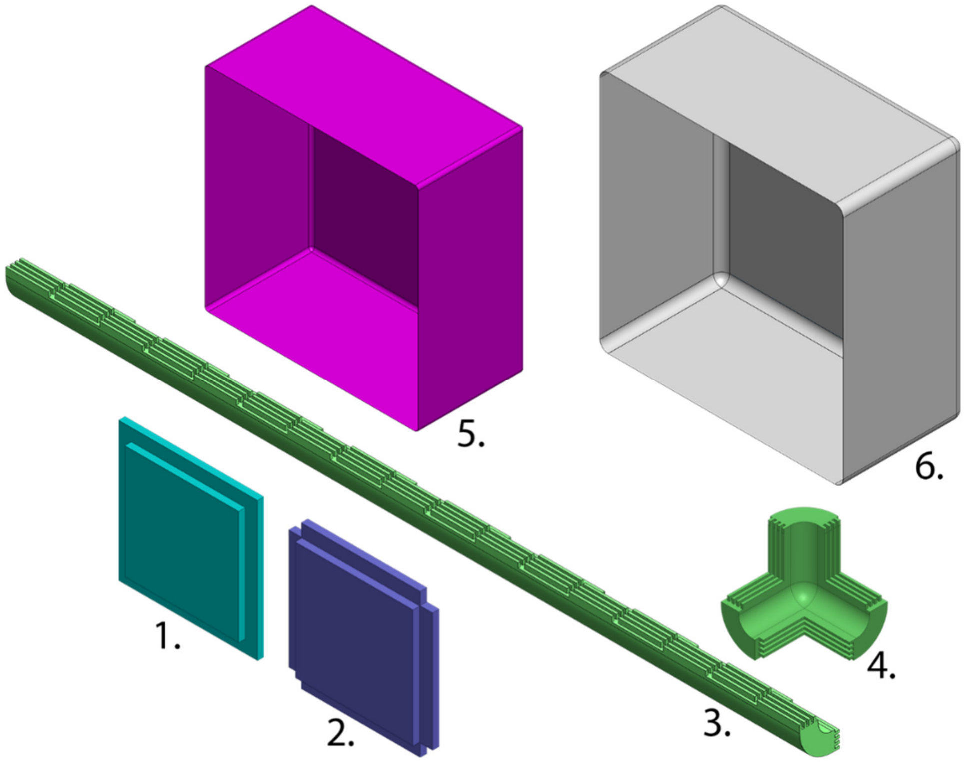

Figure 20: Basic components of the insulation system NIC_10 (1) and (2) VIP configuration, (3) Frame edge, (4) Frame vertex, (5) Liner, (6) External jacket

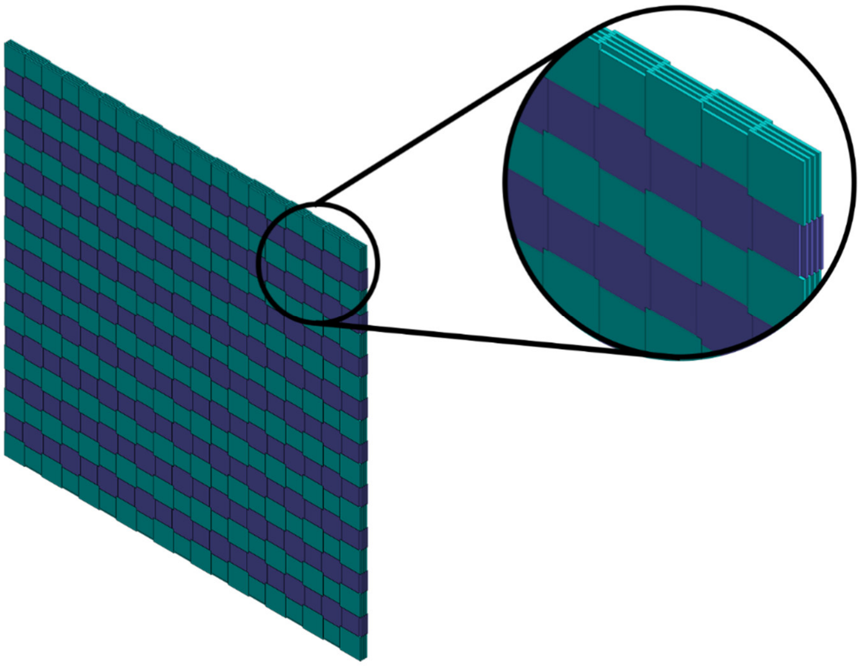

Figure 21: Isometric view of the insulation system NIC_10

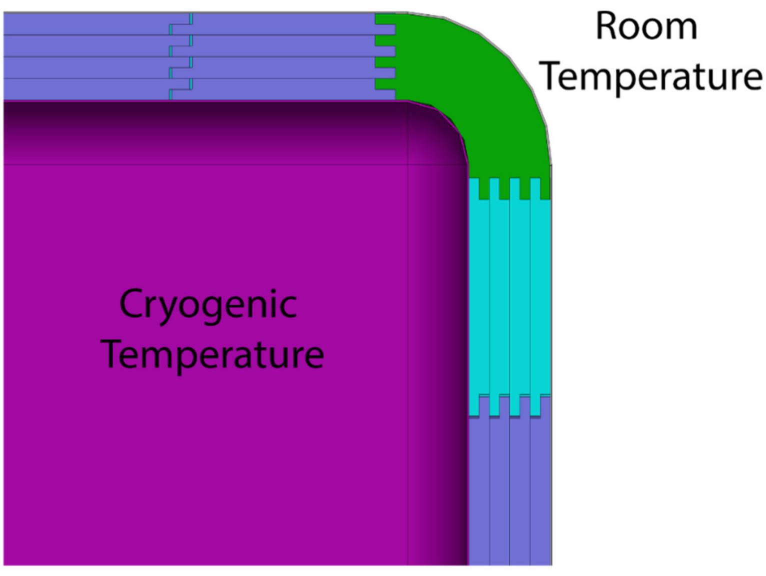

Figure 22: Side view of insulation system NIC_10

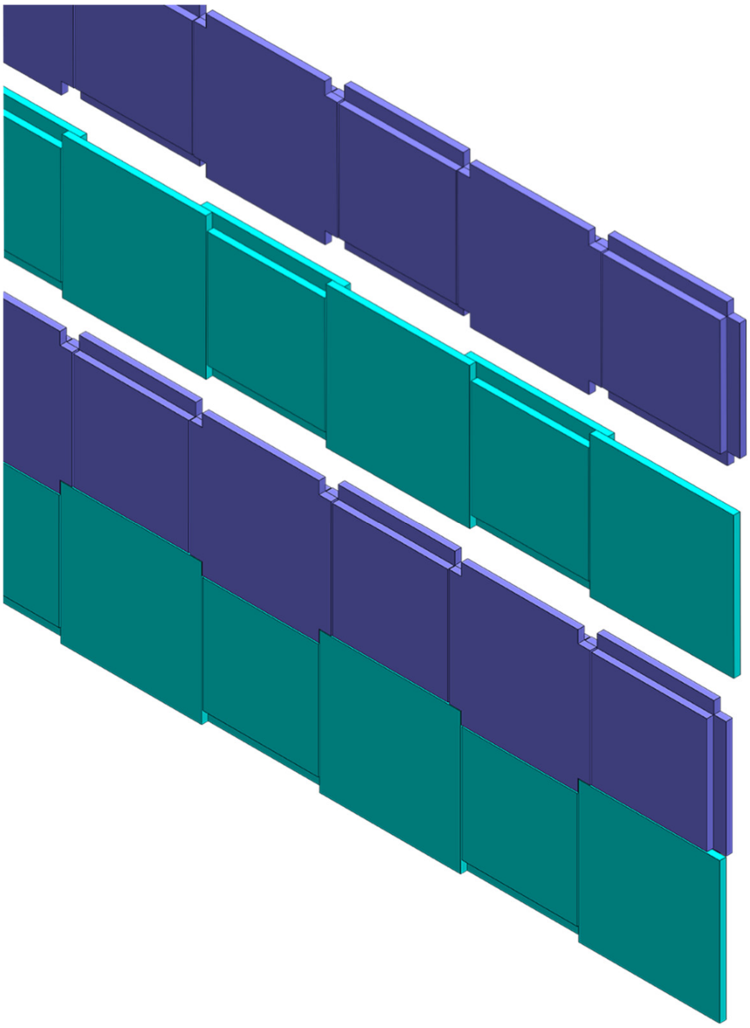

Figure 23: Assembly isometric view of the VIP modules (NIC 10)

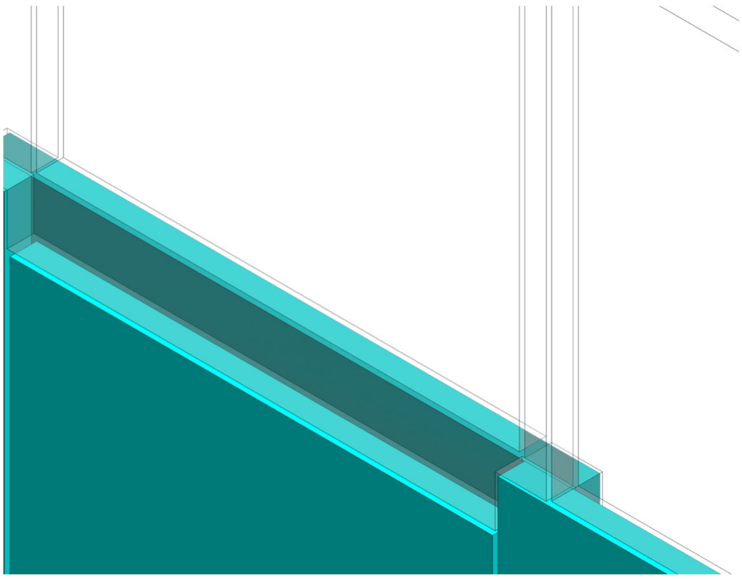

Figure 24: Detailed view of VIP joint (NIC 10)

3.10.2 Description

The novel insulation concept NIC_10 aims to achieve thermal insulation using a combination of vacuum insulation panels arranged in a specific geometric pattern. The system consists of two distinct VIP configurations that interlock to form the insulation layers. The main components are listed below:

- **Two VIP configurations** (Figure 20 (1) and (2)): These consist of an envelope made from one or a combination of the following materials: Glass/Epoxy (G-10CR, G-11CR), Polyether Ether Ketone (PEEK), Polyimide, and Polybenzimidazole (PBI) filed with Hollow Glas Microspheres (HGM) K1 grade. The panels are arranged in an alternating pattern, creating a mosaic structure. The shape of each configuration allows them to fit together, minimizing thermal bridges by joint overlapping.
- **Frame structure**: A rigid frame, comprising edge (Figure 20 (3)) and vertex (Figure 20 (4)) components, encases the VIP arrangement. This frame provides support and maintains the precise positioning of the VIPs. Additional frame structure may be needed for structural support.
- **Liner**: A liner made of austenitic stainless steel (Figure 20 (5)) is incorporated within the internal part of the reservoir, serving as a barrier against LH_2 permeation.
- **External jacket**: The entire assembly is enclosed in an external jacket made of austenitic stainless steel (Figure 20 (6)), providing protection against environmental elements and mechanical damage.
- **VIP joints**: As shown in Figure 24, special attention is given to the joints between VIPs. These areas are critical for thermal performance and are likely to be filled with secondary insulation materials to reduce heat transfer further and keep uniform joint gaps.

The geometric design of the VIPs and their interlocking arrangement are the key aspects of this concept, aiming to minimize thermal bridging while maintaining the possibility of maintenance activities. The modular section replacement approach for maintaining VIP insulation systems can enable targeted access and replacement of specific areas without disassembling the entire structure. This method divides the global insulation system into removable sections composed of VIP units.

The external jacket must be designed to access panels using secure and reusable fasteners and gaskets. Beneath the jacket, each module has a dedicated placement mechanism for secure positioning during operation and easy disassembly for maintenance.

The panels are designed to be removed and replaced by new units. Specialized tools are likely to be developed to ensure the safe maintenance of these modules. The interfaces between the panels must have sealing systems to prevent thermal bridging while allowing for easy disengagement for maintenance.

Although offering advantages, such as targeted maintenance and possibly reduced system downtime, this method introduces additional complexity. A broader intervention in the adjacent panels may be needed to reach the VIP that needs to be repaired. Despite these challenges, the modular replacement approach can be promising for maintaining complex VIP insulation systems.

3.10.3 Advantages

- The modular structure allows for easy scaling and customization to fit various shapes and sizes
- The thermal insulation performance is optimized thanks to the interlocking VIPs, which minimize thermal bridges and potentially offer superior insulation compared to traditional flat VIP arrangements
- The unique shape of the VIPs, combined with the frame structure, likely provides enhanced structural stability to the insulation system
- The production of the VIPs can be parallelized
- The VIPs can be produced and assembled in an industrial environment, allowing consistent quality control and reducing on-site installation time
- The modular layout might facilitate easier identification and replacement of damaged sections
- The degradation of a single module does not substantially impact the overall performance of the system
- Good fire resistance of the hollow glass microspheres, no toxic emissions when burned
- The design is effective in preventing air condensation
- Hollow glass microspheres can be recycled, producing low waste

3.10.4 Disadvantages

- The complex shapes of the VIPs and especially the frame components may present challenges in manufacturing and increase production costs
- The interlocking design likely requires high precision during installation to ensure proper fitting and optimal performance
- Different thermal expansion coefficients between the VIPs, frame, and jacket materials could lead to stress or gaps in the system over time
- The complex geometry at edges and corners may present difficulties in maintaining consistent insulation performance across the entire structure.
- Replacing individual components could be challenging due to the interlocking nature of the system
- The capital expenditure is significantly higher compared to conventional LH_2 storage systems due to the cost of hollow glass microspheres and the complex manufacturing of interlocking VIPs

3.11 Novel insulation concept NIC_11

Insulation concept name:	VIP suspension kit
Concept ID:	NIC_11
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.11.1 Sketch

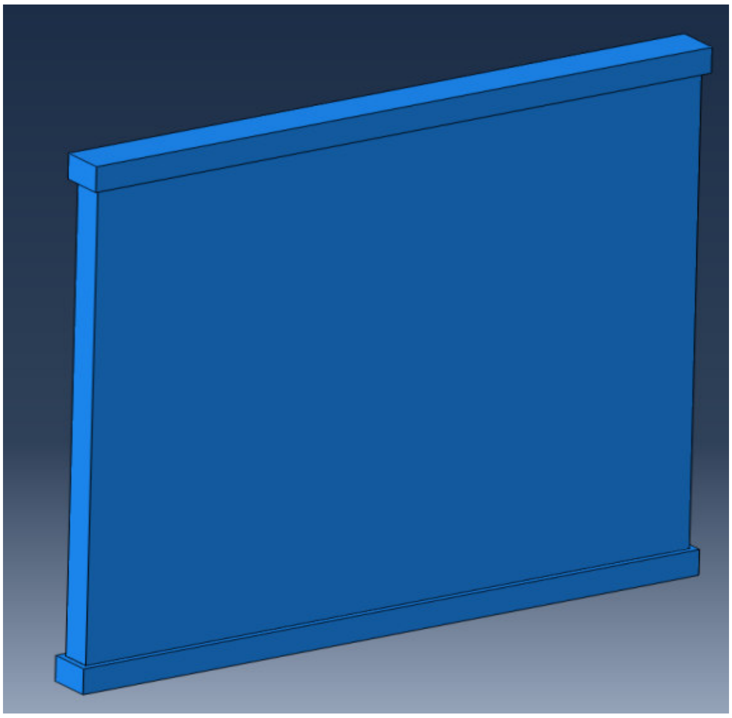

Figure 25: Bracket and VIP assembly (NIC 11)

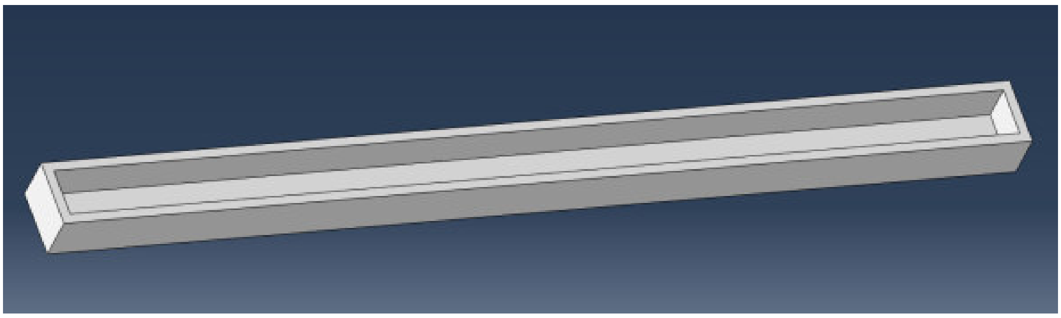

Figure 26: Bracket (NIC 11)

Figure 27: Braided line (NIC 11)

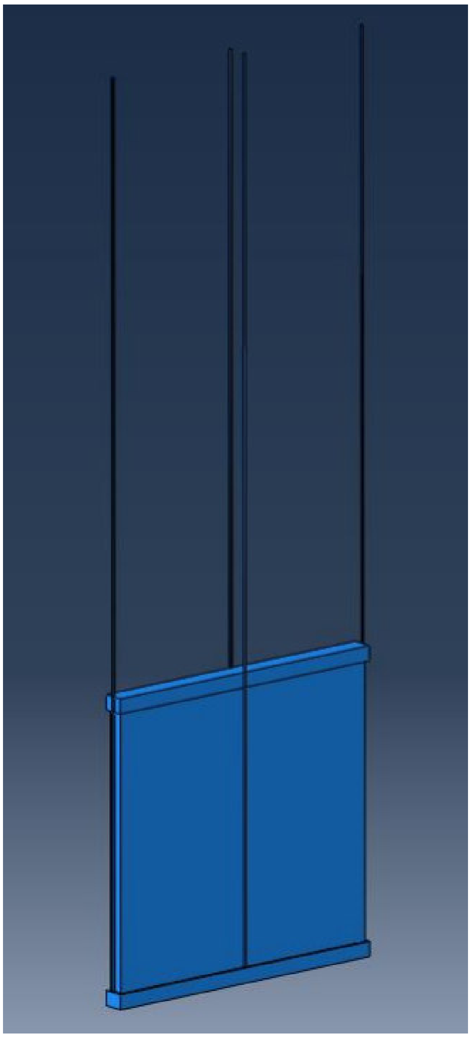

Figure 28: VIP, bracket, and line assembly (NIC 11)

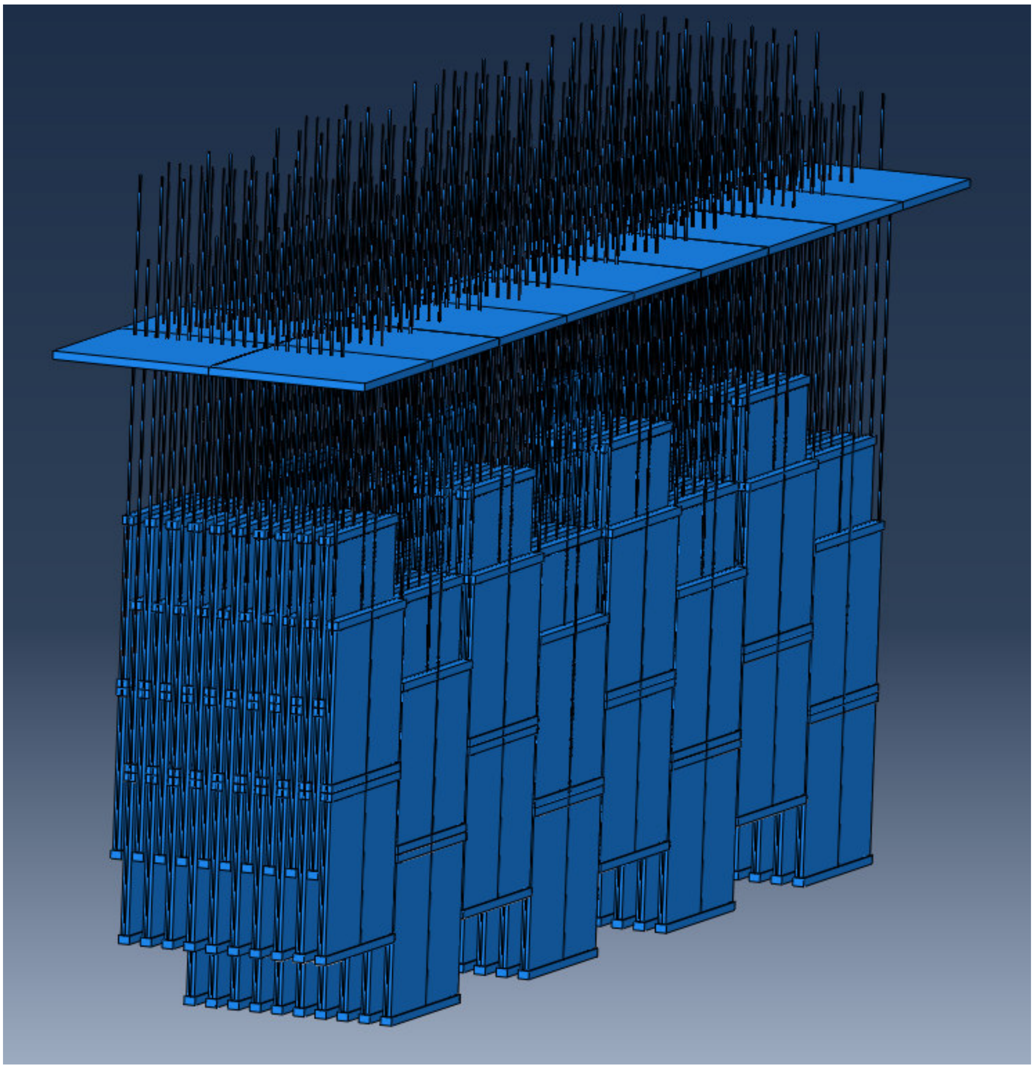

Figure 29: Assembly of multiple VIPs, brackets, and lines (NIC 11)

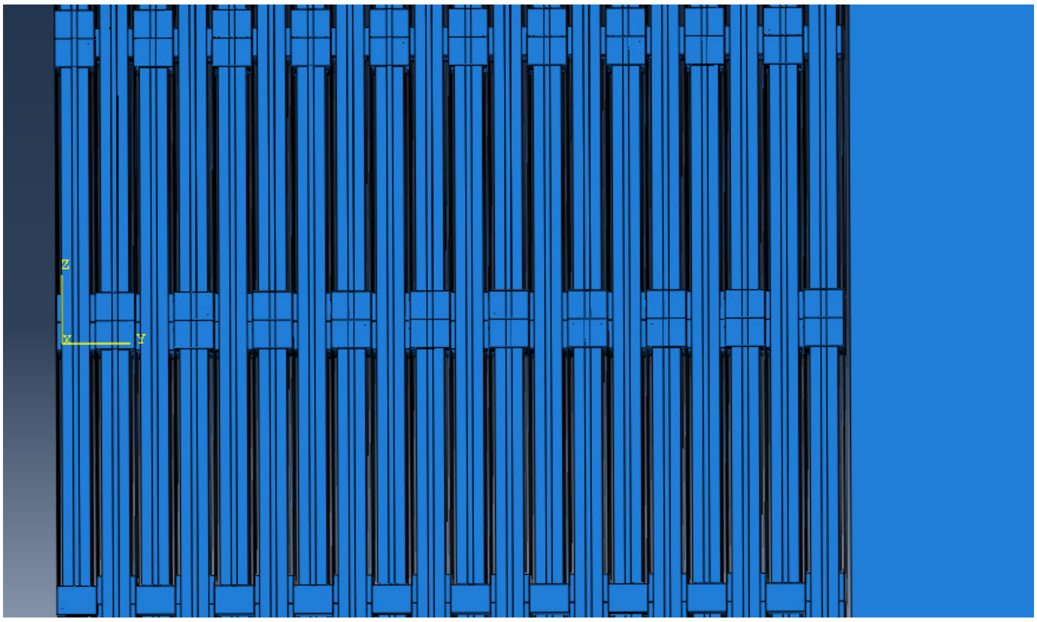

Figure 30: VIP and tank assembly (NIC 11)

3.11.2 Description

Two brackets made from an insulating material (e.g., Teflon) are placed on the edges of the VIPs. Braided lines (Nylon, as those used in fishing, or steel for strength) are passed around the VIP and bracket assembly, and an extension to the top is created. The extensions can be tied (anchored) on the top of the hydrogen tank shell or on a scaffold. Each panel can be tied separately, or a row of panels can be tied together with the same lines. Glasswool fibers can be used between the panels and brackets. The brackets can be a loose fit to account for thermal expansion. Bracket size can be larger for horizontally placed VIPs, for example on the tank roof.

Each line can hold a significant weight depending on the diameter. In general, 8 kg per line is a good estimate. For a 1 × 1 × 0.05 m^3 panel that weights approximately 6 kg, the support from multiple lines is more than enough. Adding more lines can also improve the stability and reduce vibrations. The brackets can be rounded at the edges to avoid line wear. Since each panel or each row is supported independently from the rest, temperatures will be almost equal locally and thermal expansion can be handled properly. This assembly can use nonmetallic materials to support the VIPs, thus reducing the thermal conductivity of an equivalent metal supporting structure. Finally, the panels will be in contact with each other vertically, so suspension is partial and considered a support mechanism to reduce stress on the lower rows.

VIPs are mounted on a tank with spherical configuration. The sphere is the shape with the lowest surface to volume ratio. It provides a long path for the thermal bridges, potentially lowering overall heat flow to the liquid hydrogen.

3.11.3 Advantages

- Modular and scalable design
- Lightweight support structure
- Limited increase in overall thermal conductivity
- Good dampening for the insulation overall vs vibrations
- Possibly safe in the case of failure of a braided line thanks to the multiple support points

3.11.4 Disadvantages

- Possible installation issues
- Maintenance depends on top anchor assembly (reaching the bottom row can be difficult)

3.12 Novel insulation concept NIC_12

Insulation concept name:	Insulation optimization
Concept ID:	NIC_12
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	Fibers / Vacuum / Hollow glass microspheres

3.12.1 Sketch

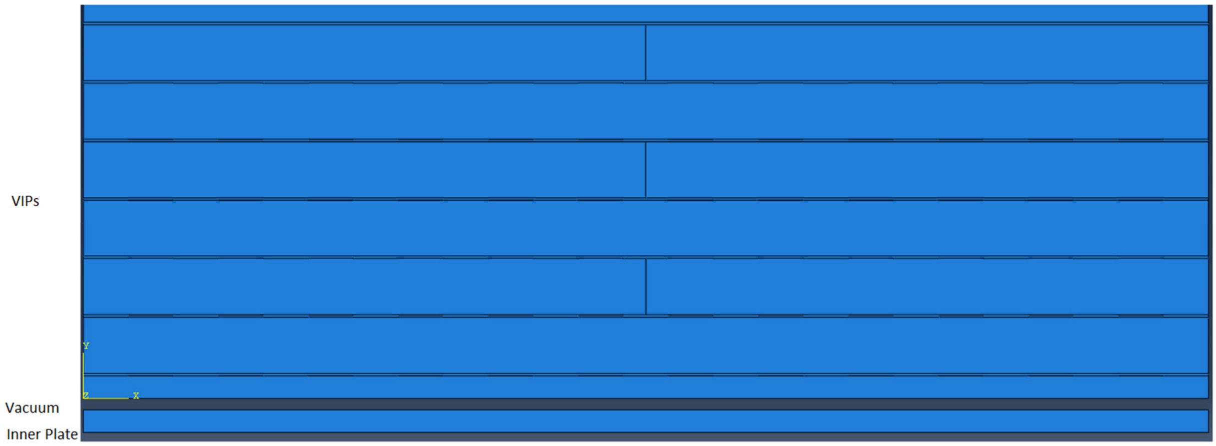

Figure 31: Assembly of VIPs with vacuum (NIC 12)

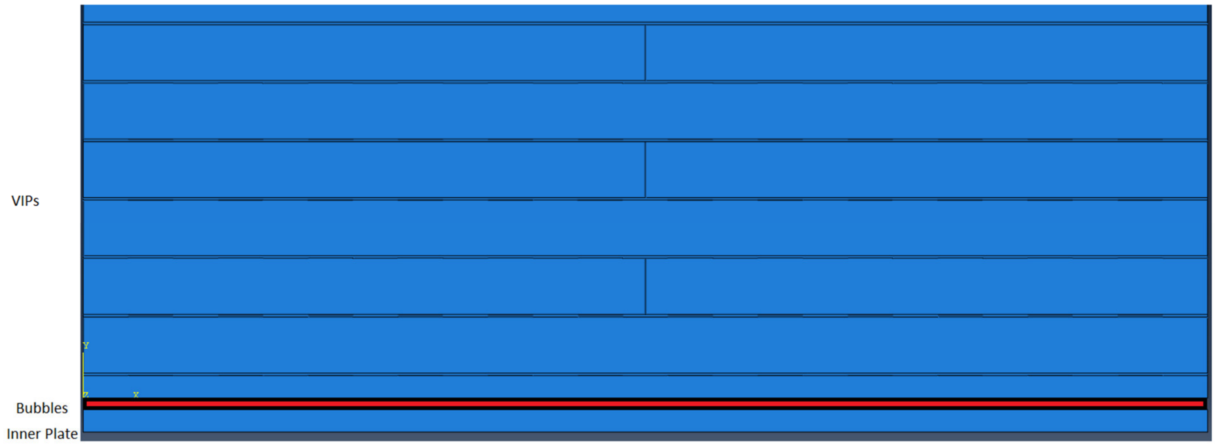

Figure 32: Assembly of VIPs with bubbles in the canal (NIC 12)

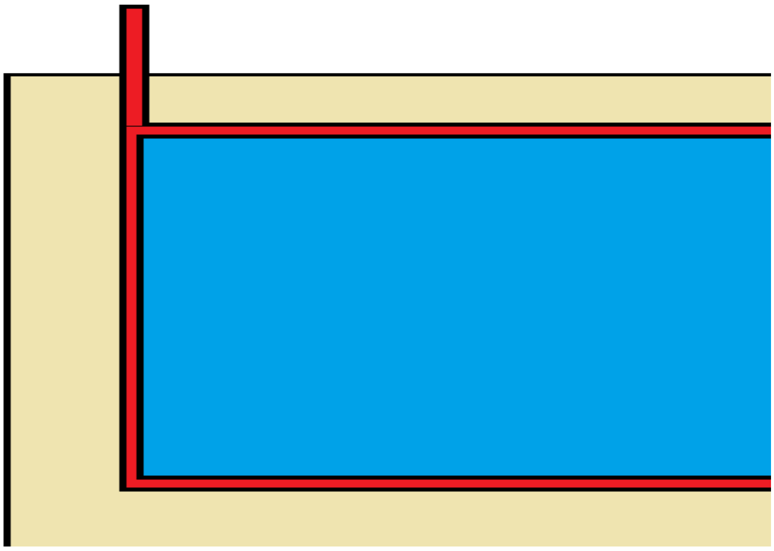

Figure 33: Overflow tank for bubbles (NIC 12)

3.12.2 Description

A canal with hollow glass microspheres is placed under vacuum conditions between the VIP assembly and the inner plate. To keep the vacuum, a nonmetallic membrane layer is required between the VIPs and the inner tank. The VIP placement mechanism can be the same as NIC_11 or other proposals. Canal size can be estimated through calculations. Adding a HGM canal will help keep the contact between the insulation and the inner plate when the plate contracts during thermal cycles. Additionally, at the top of the structure, a chamber filled with HGMs is created to provide more glass microspheres and fill the area during contraction, eventually giving space for them when the system goes back to ambient temperature (overflow tank).

Initial simulations with vacuum in the canal instead of glass bubbles microspheres that radiation in the empty space transfers a significant amount of heat when the distance is small (inverse square law). Using microspheres instead of fibers (usually employed in vacuum insulation systems) in the canal is suggested to achieve better thermal performance. Simulations showed that this canal filled with microspheres under vacuum performs the same as the initial 2D configuration with VIPs and fibers touching the inner plate but with the advantage of better contact during thermal contractions.

3.12.3 Advantages

- Modular and scalable design
- No need for VIP contact management with the inner plate
- No penalty in thermal conductivity after canal size estimation

3.12.4 Disadvantages

- Pump required to maintain vacuum
- Higher design complexity and cost

3.13 Novel insulation concept NIC_13

Insulation concept name:	Hexagonal and spherical VIPs
Concept ID:	NIC_13
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.13.1 Sketch

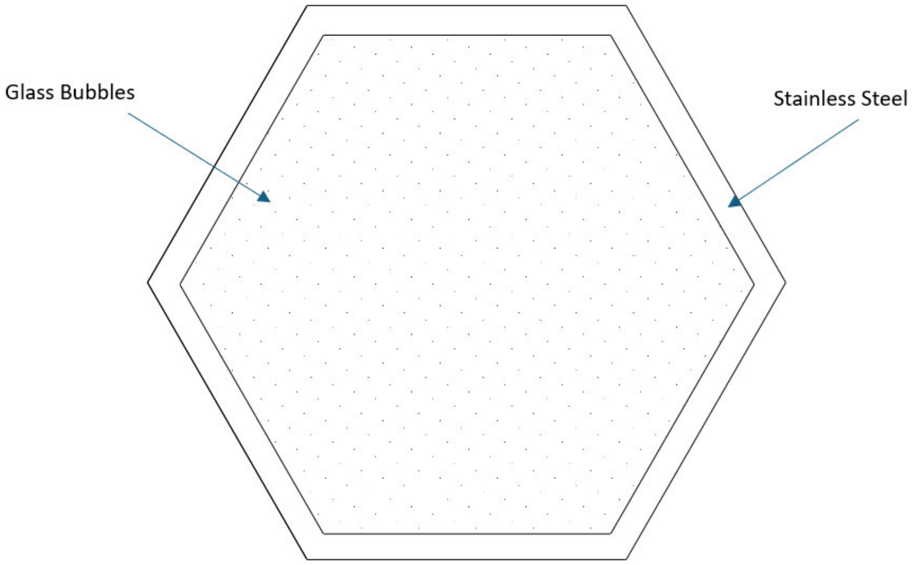

Figure 34: Exagonal VIP (NIC 13)

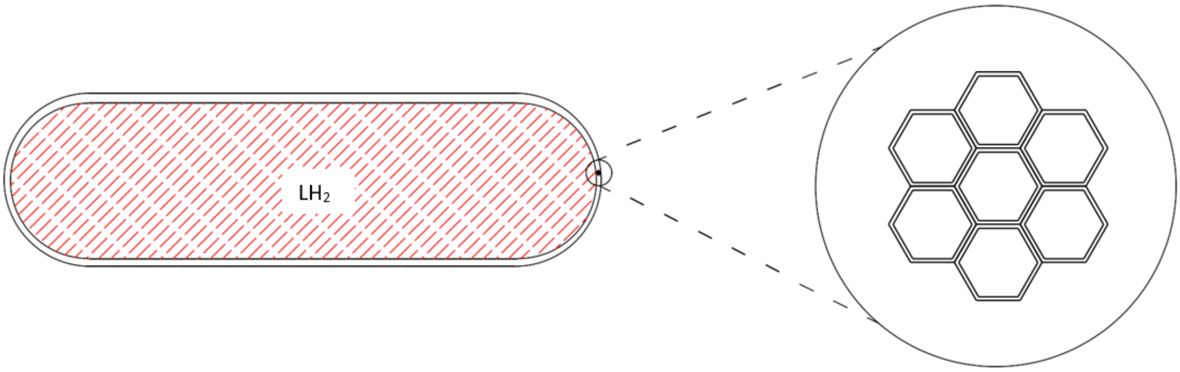

Figure 35: Assembly of hexagonal VIPs (NIC 13)

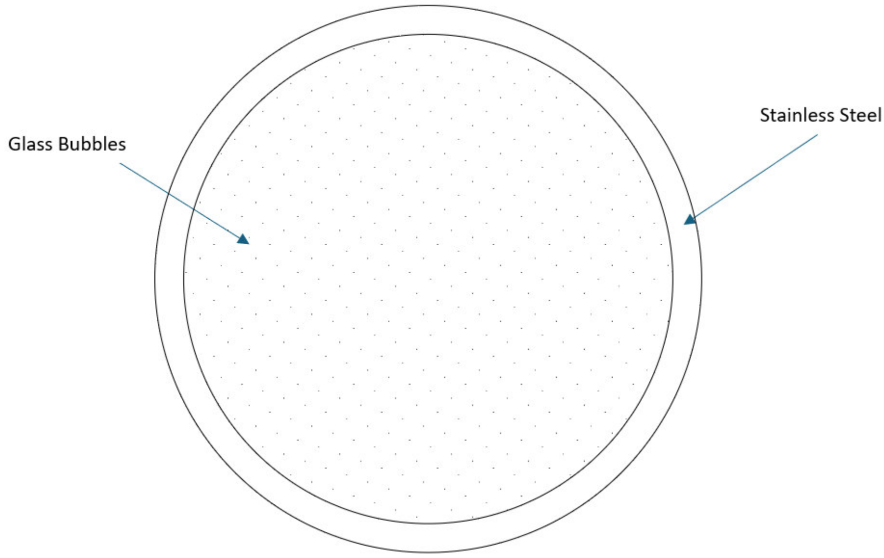

Figure 36: Spherical VIP (NIC 13)

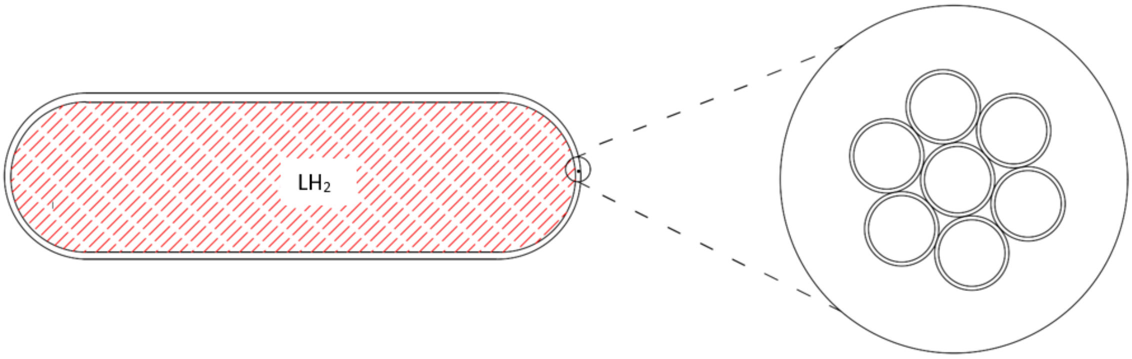

Figure 37: Assembly of spherical VIPs (NIC 13)

3.13.2 Description

The tank has a cylindrical shape. The envelope of the vacuum insulation panels is stainless steel, and the core material is made of hollow glass microspheres. In order to minimize the effect of thermal bridges, glass wool is placed between the hexagonal or spherical VIPs.

The hexagonal shape exhibits the lowest perimeter-to-area ratio among polygons, making it more efficient in terms of material usage, and it also offers greater ease of assembly compared to a spherical configuration. However, the hexagonal geometry may experience angular distortion as a result of applied loads or weight-induced deformation.

The sphere possesses the lowest surface-to-volume ratio of all geometric shapes, thereby minimizing thermal bridges and potentially reducing the overall heat transfer to the liquid hydrogen.

3.13.3 Advantages

- Modular and scalable design
- Efficient thermal performance
- The structure is adaptable to various tank shapes
- Lightweight support structure

3.13.4 Disadvantages

- Mechanical distortions of hexagonal and spherical VIPs can be significant
- Maintenance activities can be difficult

3.14 Novel insulation concept NIC_14

Insulation concept name:	Fluxed single gap with VIPs
Concept ID:	NIC_14
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.14.1 Sketch

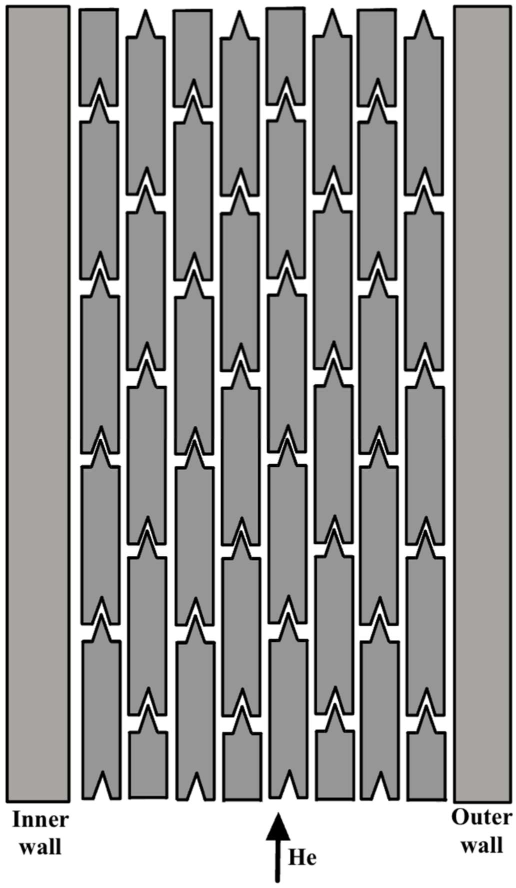

Figure 38: NIC_14 cross section: the VIP insulation between inner (left) and outer (right) walls is provided by a slightly pressurized helium flow and flexibly connected VIPs

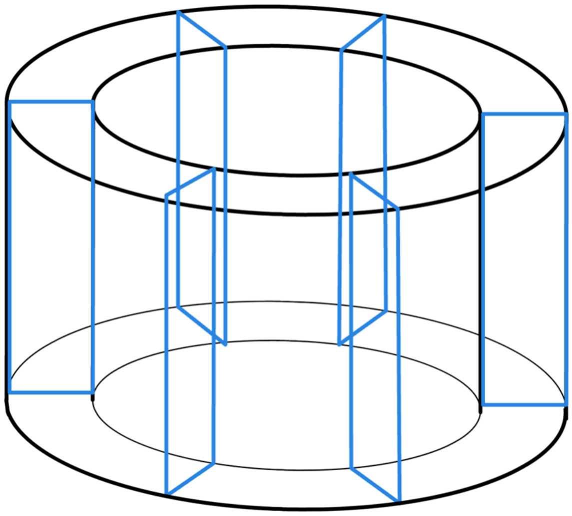

Figure 39: NIC_14 with possible sweeping gas partitioning by membranes

3.14.2 Description

The insulation system is made up of staggered insulation panels that are located in a gap between an inner and outer wall. The inner wall is a tight barrier for LH_2 (e.g., steel alloy compatible with LH_2). The outer wall is a tight barrier for air (e.g., concrete lined with plastic film); the outer wall is not suitable for regular contact with LH_2 but is somehow "resilient" in case of occasional contact, i.e., prevents massive liquid spread, so that it is damaged, but the structure does not collapse. Presence of air and humidity in the gap (ambient air may enter the gaps among VIPs in the installation phase and even during operation if leaks occur in the outer wall) is prevented by fluxing. Thus, what is proposed is shown in Figure 38:

- To operate the gap with a slight overpressure compared to atmospheric conditions (e.g., < 100 Pa) with a sweeping gas flow
- To use helium in closed cycle as sweeping gas. Indeed, this allows to avoid solidifications and liquefactions in the insulation space closer to the cold wall (that could take place using nitrogen or hydrogen)

The gap can be partitioned by suitable thin membranes into sections, as described in Figure 39. Here, the sweeping gas normally flows separately in the different sections, thus making leak detection possible for each section.

3.14.3 Advantages

- Prevents air/humidity ingress and freezing/condensation, which may lead to thermal bridges and damage of the insulation materials
- Simple configuration with a single layer and a single type of insulation material
- Allows detection of small leakages (loss of H_2 by analysis in sweep gas output and loss of He to air by pressure monitoring)

3.14.4 Disadvantages

- Cost of He for large volumes and makeup (even if in closed cycle)
- Additional heat loss by convective heat transfer of He flow

3.15 Novel insulation concept NIC_15

Insulation concept name:	Fluxed two gaps with VIPs
Concept ID:	NIC_15
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.15.1 Sketch

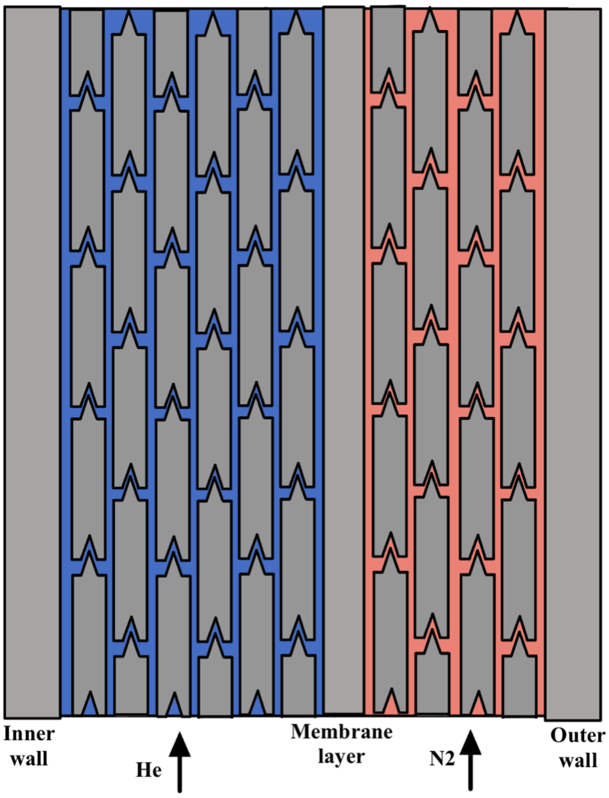

Figure 40: NIC_15/A with two layers of gaseous sweeping over VIPs. The second “hotter” (red) layer could benefit from the use of a cheaper nitrogen circulation

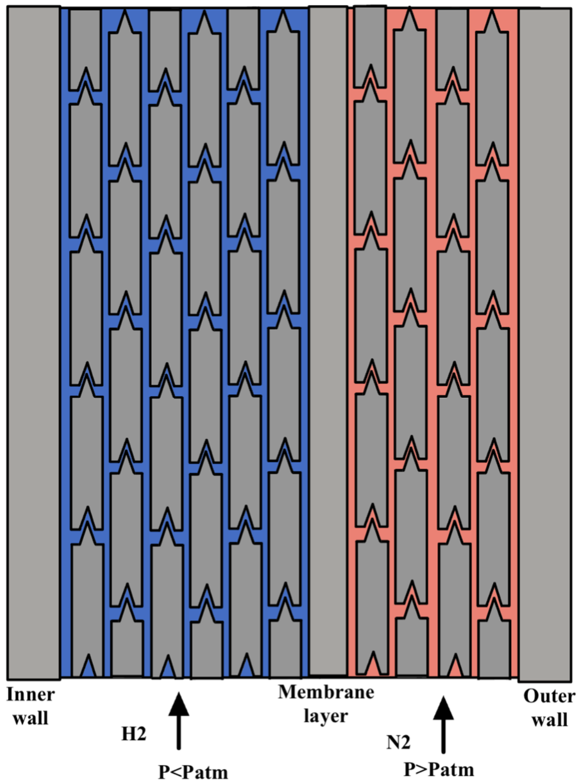

Figure 41: NIC_15/B where a first VIPs layer in a H_2 flow slightly below atmospheric pressure is followed by a second layer of a slightly pressurized N_2 flow

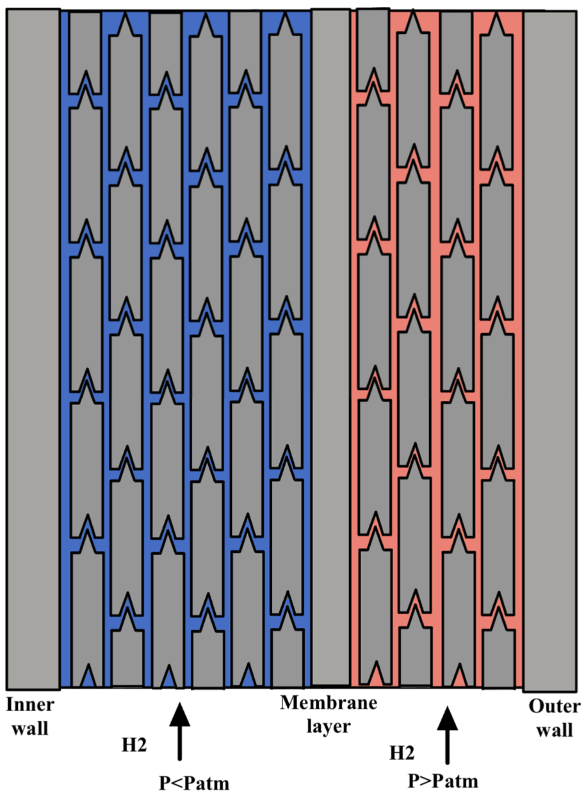

Figure 42: NIC_15/B where both gas sweepings are of H_2, the first with a slight vacuum, the second with a slight overpressure

3.15.2 Description

Starting from concept NIC_14, in an optimization perspective, this concept introduces a separating wall (non-load bearing, of a material not suitable for normal contact with LH_2) that divides the gap perpendicularly to the heat flow direction. This wall creates two zones or regions within the gap, as shown in Figure 40:

- A “cold” zone, where the colder part of the thermal gradient is provided by VIPs being fluxed in their gaps by helium at a slight overpressure compared to atmosphere and in a closed cycle
- A “hot” layer, where VIPs are immersed in a gaseous flow other than helium (e.g., hydrogen or nitrogen) in slight overpressure

Having two insulation zones where VIP gaps are fluxed by two different gases allows also for alternative configurations to avoid the use of helium.

Alternatives NIC_15/B and NIC_15/C both feature two VIPs-insulated layers where:

- In the “cold” zone, a hydrogen sweeping in a slight vacuum is used (few Pa to tens Pa below atmospheric pressure) to avoid condensation
- In the “hot” zone, a circulating flow of a gas other than helium (e.g., nitrogen in NIC_15/B or hydrogen in NIC_15/C) is applied, with tens or hundreds Pa overpressure

The two alternatives are reported respectively in Figure 41 and Figure 42.

3.15.3 Advantages

- Prevents air/humidity ingress and freezing/condensation, which may lead to thermal bridges and damage of insulation materials
- In the case of failure of the separating wall, can be operated as the concept NIC_14
- Allows detection of small leakages (loss of H_2 by analysis in inner sweep gas output, loss of atmosphere by pressure monitoring)
- Reduces or eliminates the requirement for helium

3.15.4 Disadvantages

- Higher complexity of the configuration
- Additional heat loss by convective heat transfer (less than NIC_14)

3.16 Novel insulation concept NIC_16

Insulation concept name:	Fluxed two gaps with insulating layer and VIPs
Concept ID:	NIC_16
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	Porous compact material (inorganic or polymeric)

3.16.1 Sketch

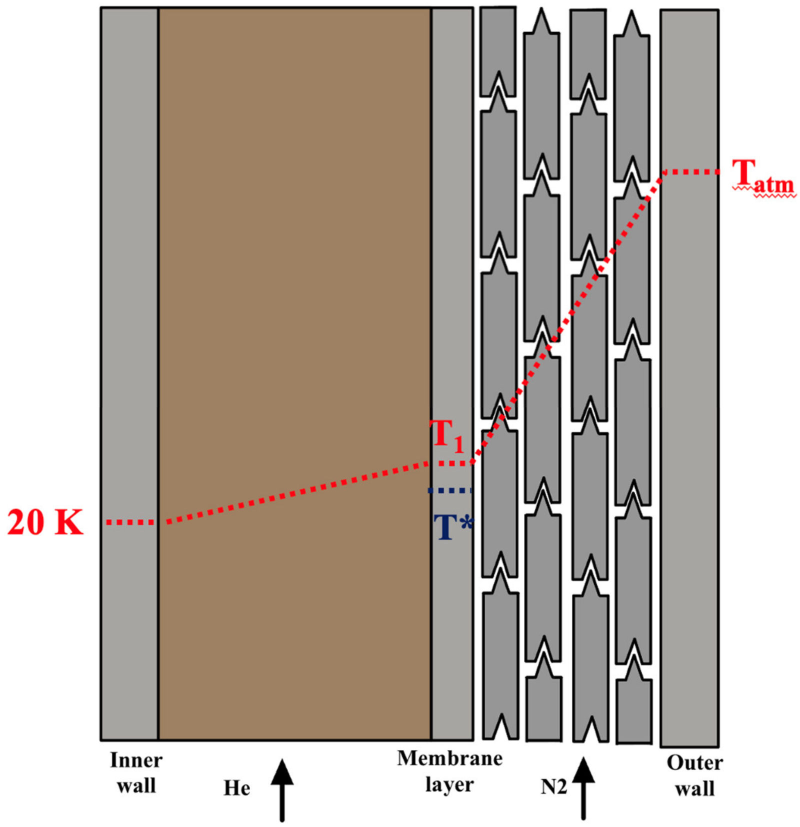

Figure 43: NIC_16 insulation concept where a limited-thickness first layer (to be specifically defined and possibly fluxed with He or H_2) covers a temperature gradient such that then T >T* (saturated conditions for the gas) and it is possible to have a region where VIPs are immersed in a H_2 or N_2 flux

3.16.2 Description

An alternative design of NIC_15 where the cold zone insulation system is not VIP-based but a fluxed continuous layer of granular or fibrous material. The cold zone has a thickness that is minimized based on thermal considerations. A schematic is shown in Figure 43:

- The "cold" zone, composed of a porous compact material (inorganic or polymeric) achieves a great temperature gradient that rises temperatures above the condensation point of the fluid in the hot zone. The cold layer will still need a He (slightly pressurized) or H_2 (slightly depressurized) fluxing flow (see NIC_15)
- The "hot" zone, where VIPs are present, has a gas sweeping of H_2 or N_2 (see NIC_15).

The feasibility of this concept depends on the availability of a nanoporous material with insulation performances good enough to keep the thickness of the first layer within a reasonable limit.

3.16.3 Advantages

- Prevents air/humidity ingress and freezing/condensation, which may lead to thermal bridges and damage of insulation materials
- In case of failure of the separating wall, can be operated as NIC_14
- Allows detection of small leakages (loss of H_2 by analysis in inner sweep gas output, loss of atmosphere by pressure monitoring)
- Reduces or eliminates the requirement for helium
- Potentially more compact than NIC_15
- Reduces need of insulating material in the cold insulating layer

3.16.4 Disadvantages

- Higher complexity of the configuration
- Additional heat loss by convective heat transfer (less than NIC_14)

3.17 Novel insulation concept NIC_17

Insulation concept name:	Tongue and groove VIPs with helium between panels
Concept ID:	NIC_17
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.17.1 Sketch

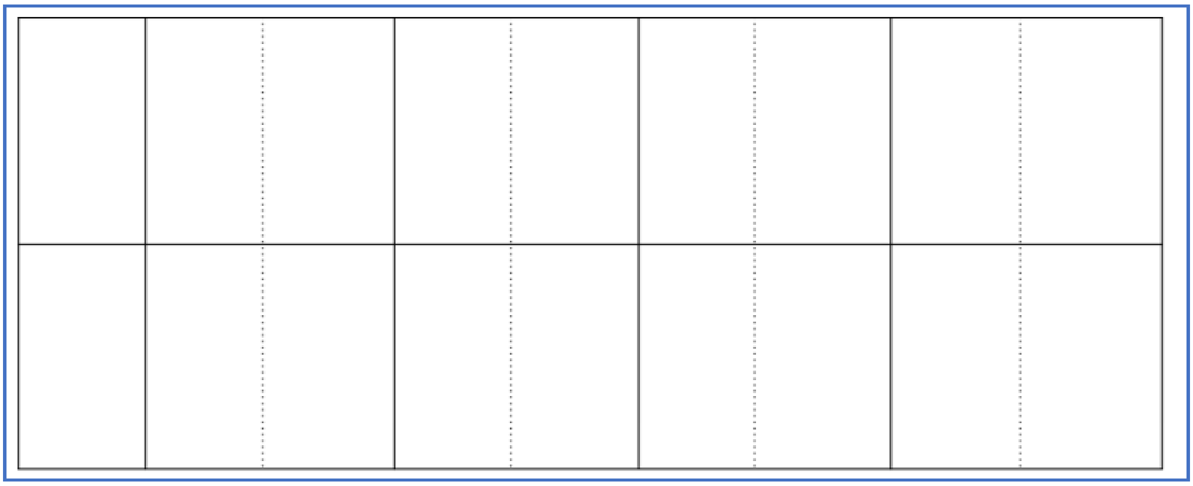

Figure 44: Front view of VIPs connected via tongue and groove method (NIC 17)

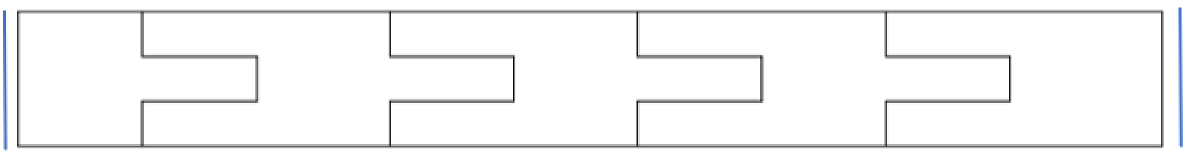

Figure 45: Side view of VIPs connected via tongue and groove method (NIC 17)

3.17.2 Description

This insulation system is composed of square vacuum insulation panels mounted via tongue and groove method and surrounded by a frame (blue line). Helium between panels allows to replace panels without heating up the entire tank. To replace the panel an overpressure of helium should be created with a use of small helium container.

Recommendations based on the manual handling regulations for a single-handed operation:

- Weight should not exceed 12-23 kg
- Size up to 1.2 m

Recommendations based on the "one fits all" production and installation approach:

- Width 1.2 m (2.4 m in the case of maritime applications)

3.17.3 Advantages

- Tongue and groove joints allow for easy maintenance
- Tongue and groove joints increase the thermal resistance of the insulation system
- Presence of helium reduce the time needed for panel replacement

3.17.4 Disadvantages

- Design requires accurate calculations of the thermal expansion of the panel in order to leave enough space for the tongue and groove joint
- Presence of thermal bridges
- Requires an additional small helium container

3.18 Novel insulation concept NIC_18

Insulation concept name:	Array of panels with waffle like steel envelope
Concept ID:	NIC_18
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.18.1 Sketch

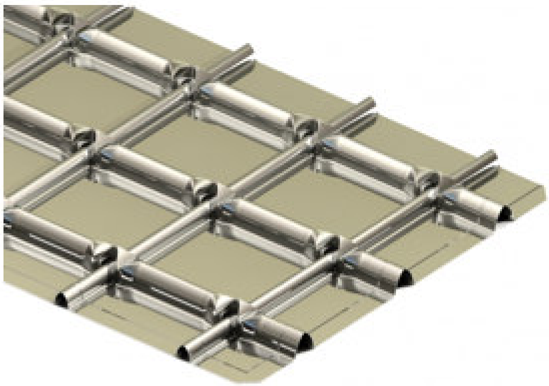

Figure 46: VIP with a waffle-like metal envelope used in the Mark III systems | GTT

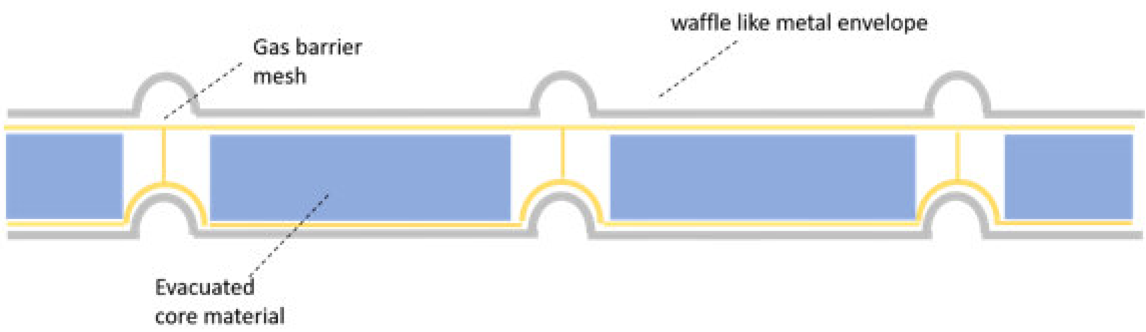

Figure 47: Side view of the array of panels with waffle like steel envelope (NIC 18)

3.18.2 Description

The insulation concept is composed of square panels surrounded by gas barrier mesh and covered with stainless steel waffle-like envelope.

Recommendations based on the manual handling regulations for a single-handed operation:

- Weight should not exceed 12-23 kg
- Size up to 1.2 m

Recommendations based on the "one fits all" production and installation approach:

- Width 1.2 m (2.4 m in the case of maritime applications)

3.18.3 Advantages

- In case of perforation of the envelope only one section is compromised
- The use of gas barrier mesh allows to exchange core insulation materials without compromising thermal performance
- The use of vacuum insulation array has been investigated in previous studies
- The use of waffle molded envelope allows for easy assembly and reduce the risk of buckling

3.18.4 Disadvantages

- Manufacturing can be challenging

3.19 Novel insulation concept NIC_19

Insulation concept name:	VIP with polyurethane foam encased in waffle like steel envelope and surrounded by pressurized helium
Concept ID:	NIC_19
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	Polyurethane foam

3.19.1 Sketch

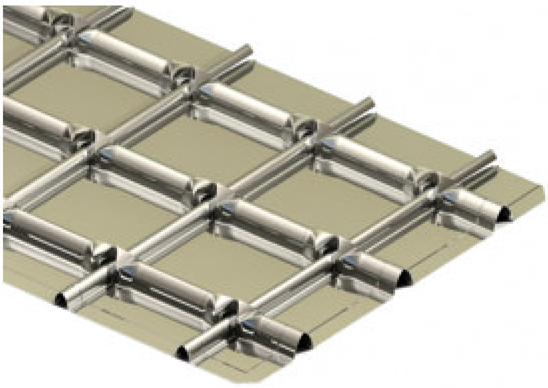

Figure 48: VIP with a waffle-like metal envelope used in the Mark III systems | GTT

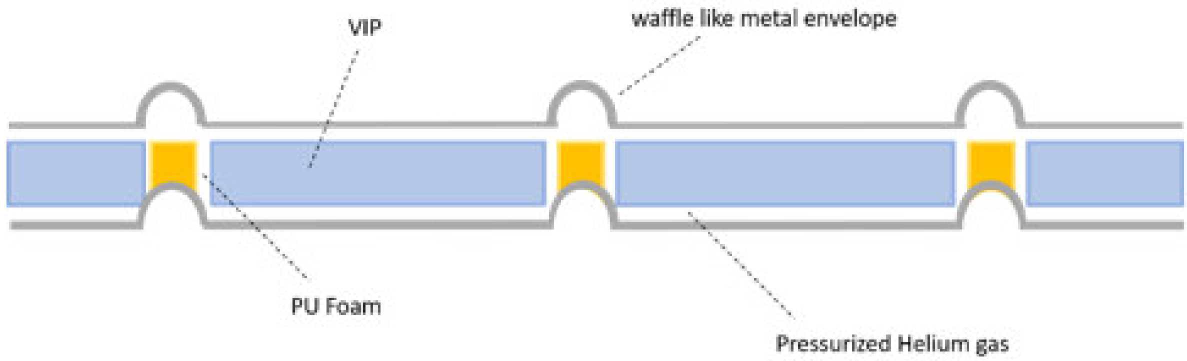

Figure 49: Side view of the array of VIP with polyurethane foam encased in a metallic envelope and surrounded by pressurized helium (NIC 19)

3.19.2 Description

The insulation concept is composed of VIPs with polyurethane foam between panels to reduce thermal bridging. VIPs and PU foam are surrounded by pressurized helium and covered with a stainless-steel waffle-like envelope.

Recommendations based on the manual handling regulations for a single-handed operation:

- Weight should not exceed 12-23 kg
- Size up to 1.2 m

Recommendations based on the “one fits all” production and installation approach:

- Width 1.2 m (2.4 m in the case of maritime applications)

3.19.3 Advantages

- The use of pressurized helium allows for replacing VIP or PU foam without heating up the entire container
- The presence of PU foam reduces thermal bridging
- The waffle-like outer envelope allows for easier assembly

3.19.4 Disadvantages

- Manufacturing can be challenging
- Requires an additional small helium container

3.20 Novel Insulation Concept NIC_20

Insulation concept name:	Modular dual-box insulation with structural membrane
Concept ID:	NIC_20
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	-

3.20.1 Sketch

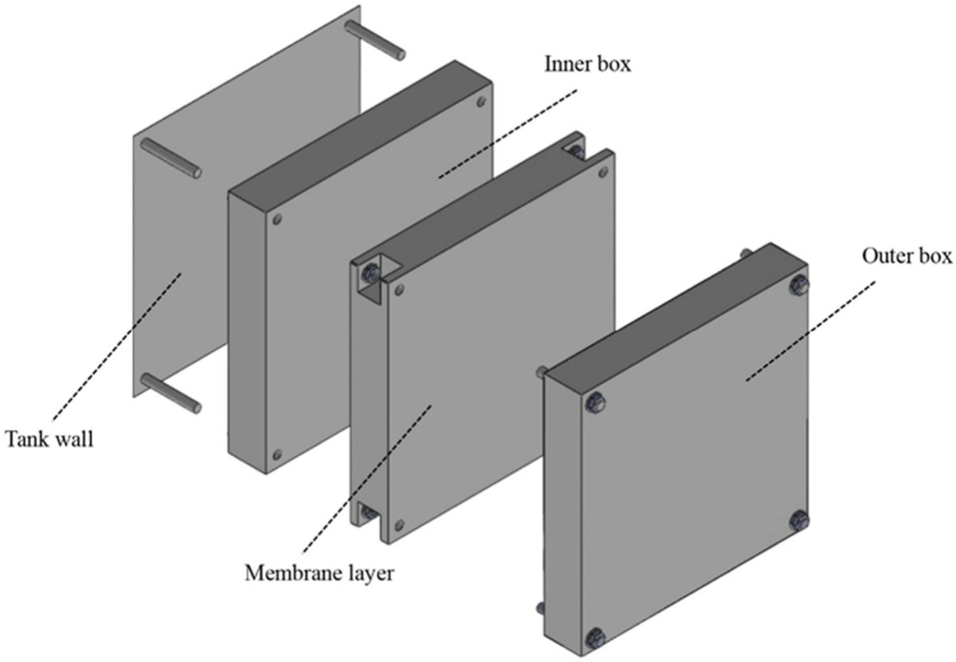

Figure 50: Exploded view of the NIC_20 modular unit with inner and outer steel boxes and membrane

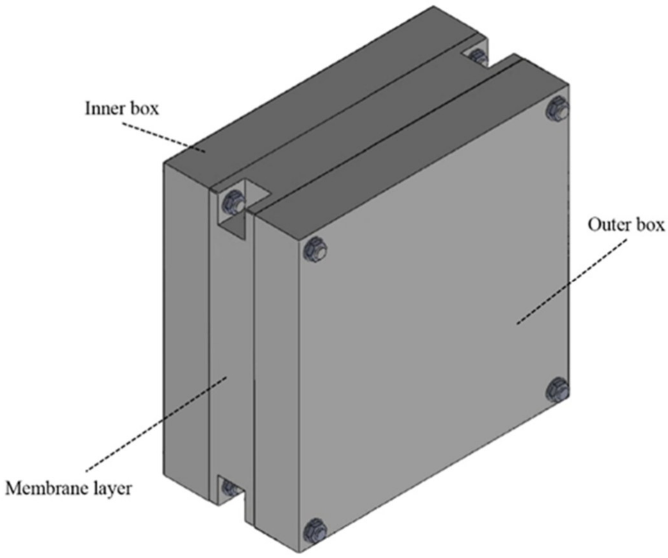

Figure 51: Assembled view of the NIC_20 modular unit with inner and outer steel boxes and membrane

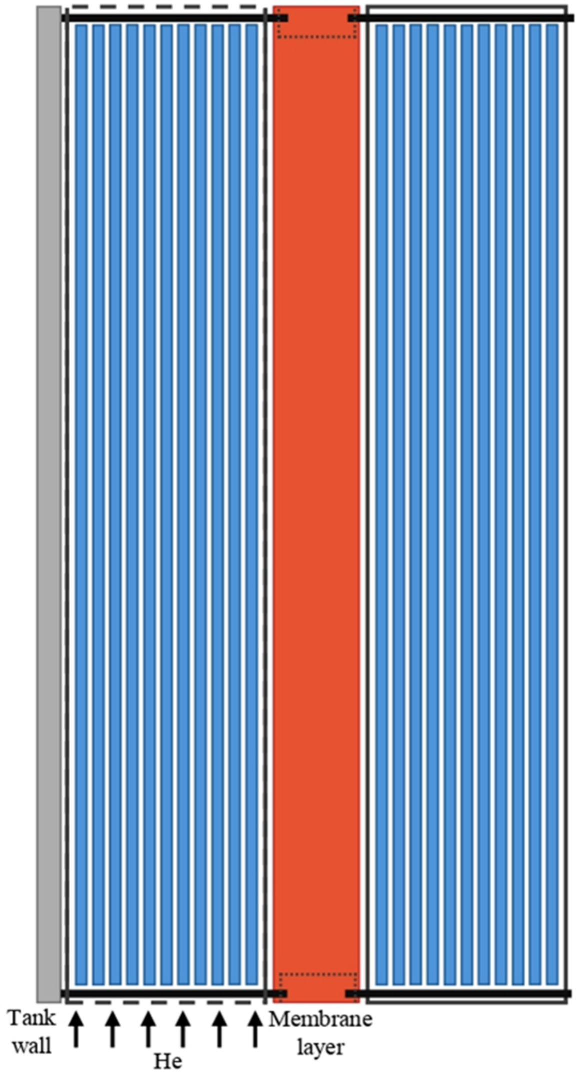

Figure 52: Cross-section of a module filled with VIPs in each box

3.20.2 Description

The NIC_20 concept builds upon the structure proposed in NIC_15, introducing a modular containment system for insulation based on two stainless steel boxes (an inner and an outer one) positioned on either side of a separating membrane. Dimensions of the boxes could be up to 3 x 3 x 0.5 m (W x H x D).

The inner box is connected to the LH_2 tank by four cylindrical metallic rods, welded to the tank wall. These supports pass through aligned holes in the membrane and are secured using cryo-compatible fasteners. Another option is to fast the bolts directly on the inner box, especially in case sweeping gas flows between the LH2 tank wall and the membrane. In this manner, the inner box would follow the contraction of the tank without being constrained to the membrane. The outer box is mounted on the opposite side of the membrane using a second set of supports, which are structurally decoupled from the inner ones to reduce thermal bridges and mechanical stresses in case of deformations.

The inner box is perforated in the upper and lower regions to enable helium (sweeping gas) circulation at a slight overpressure compared to ambient pressure. The membrane bears the structural load of both boxes (unless decoupling of the inner one is considered) and must remain above the nitrogen liquefaction temperature (–196 °C) to avoid air condensation on its external surface. The outer box does not include sweeping gas and is exposed to ambient conditions.

VIPs are placed inside both boxes and are swept by helium in the inner box and filled with ambient air in the outer one.

Each box could be equipped with sensors for monitoring temperature and pressure, enabling early detection of insulation degradation or vacuum loss. Moreover, a BOG circulation loop may be integrated within the membrane layer, the inner box, or the interspace between them, to recover cold energy from boil-off gas.

3.20.3 Advantages

- Modular structure allows prefabrication, supporting parallel production, transport, and installation.
- Mechanical robustness due to the protective steel boxes enclosing VIPs, reducing the risk of damage during handling and operation.
- Prevents air/humidity ingress and associated freezing condensation that could cause thermal bridges or insulation damage in the outer box.
- Allows selective maintenance: outer modules can be accessed and replaced individually if needed.
- Simple support system with fixed rods and gaskets, facilitating manufacturability and tank construction.
- Enables small leak detection (H_2 loss can be identified by analysis of the sweep gas output, ambient air ingress can be detected by pressure monitoring).
- Outer boxes could be vacuumized to reduce loss of vacuum risk in case of VIP failure.

3.20.4 Disadvantages

- Gas sealing at the membrane interface is critical; gaskets must remain reliable under cryogenic conditions.
- Thermal bridging risk at support points and wherever metallic components are in direct contact.
- VIPs may not fully occupy the available volume in the boxes, due to geometric constraints (e.g., coupling with the membrane) leaving small voids, thus reducing thermal performance especially in the outermost layer of the outer box due to small air-filled gaps between VIPs and the box wall (unless the box is vacuumized).
- Increased construction complexity compared to NIC_15 due to the alignment of multiple structural layers (tank wall, boxes, membrane).
- The tank wall and membrane must bear the full weight of the insulation system.
- The innermost boxes are difficult to inspect or maintain and must be done when the tank is not in operation.
- Allows local insulation performance monitoring thanks to integrated sensors.
- Thermal performance further improved through optional BOG cold recovery.

3.21 Novel Insulation Concept NIC_21

Insulation concept name:	Modular dual-box insulation divided by structural membrane with insulating layer and VIPs
Concept ID:	NIC_21
Main insulation system:	Vacuum insulation panels
Secondary insulation system:	Porous compact material (inorganic or polymeric)

3.21.1 Sketch

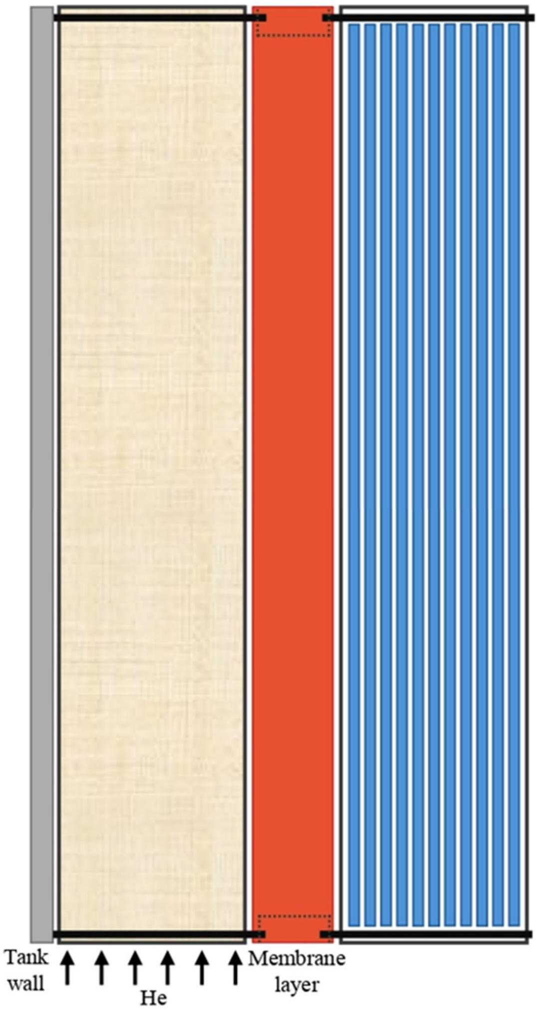

Figure 53: Cross-section of a module filled with porous insulation in the inner box and VIPs in the outer one

3.21.2 Description

NIC_21 is a variant of NIC_20 that assumes a gas tight inner containment box filled with a prefabricated compact porous material (either granular or fibrous) maintained under vacuum conditions. The cold-side of the insulation system still includes helium as a sweeping gas in the gap between the containment and the tank wall or membrane. The outer box retains the same VIP-based structure as in NIC_20.

3.21.3 Advantages

- Modular structure allows prefabrication, supporting parallel production, transport, and installation.
- Mechanical robustness due to the protective steel boxes enclosing VIPs, reducing the risk of damage during handling and operation.
- Prevents air/humidity ingress and associated freezing condensation that could cause thermal bridges or insulation damage in both inner and outer boxes.
- Allows selective maintenance: outer modules can be accessed and replaced individually if needed.
- Simple support system with fixed rods and gaskets, facilitating manufacturability.
- Outer boxes could be vacuumized to reduce loss of vacuum risk in case of VIP failure.
- Requires less sweeping gas flux compared to NIC_20, thus less time to displace air in the cold side the first time the tank is built.
- Allows local insulation performance monitoring thanks to integrated sensors.
- Thermal performance further improved through optional BOG cold recovery.

3.21.4 Disadvantages

- Gas sealing at the membrane interface is critical; gaskets must remain reliable under cryogenic conditions.
- Thermal bridging risk at support points and wherever metallic components are in direct contact.
- VIPs may not fully occupy the available volume in the boxes, due to geometric constraints (e.g., coupling with the membrane) leaving small voids, thus reducing thermal performance especially in the outermost layer of the outer box due to small air-filled gaps between VIPs and the box wall (unless the box is vacuumized).
- Increased construction complexity compared to NIC_15 due to the alignment of multiple structural layers (tank wall, boxes, membrane).
- The tank wall and membrane must bear the full weight of the insulation system.
- The innermost boxes are difficult to inspect or maintain and must be done when the tank is not in operation.
- Entire inner box is under vacuum: if vacuum is lost, a larger zone is affected compared to the localized VIPs in NIC_20, leading to a more significant loss in insulation performance.

3.22 Supports and connections SC_01

Support name: Groove-ridge connection system for VIPs
Concept ID: SC_01

3.22.1 Sketch

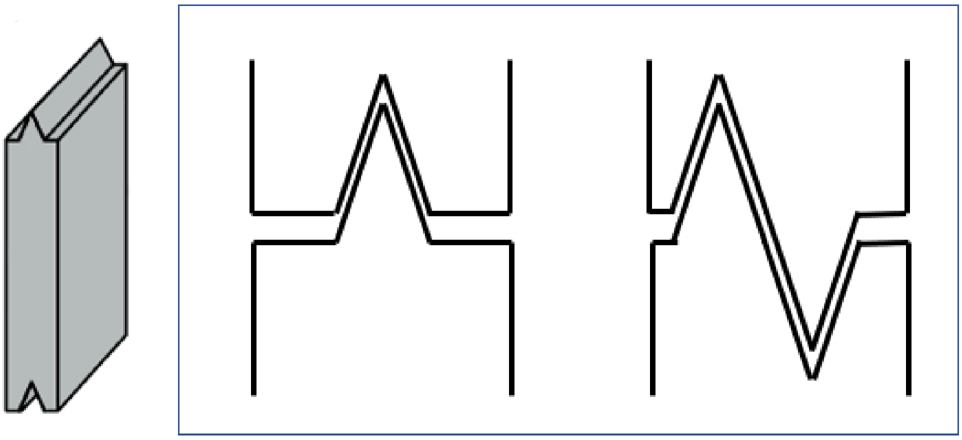

Figure 54: VIPs proposed geometry favoring the alignment and connection of the panels (shown only on two lateral sides) (SC 01)

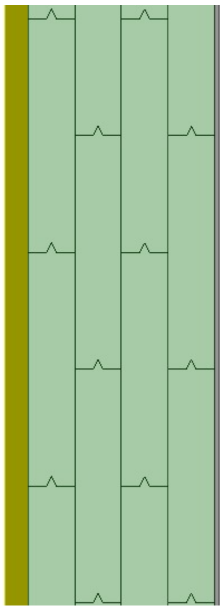

Figure 55: Insulation section showing the VIPs proposed spatial configuration (on left the inner wall and on the right the outer one) (SC 01)

3.22.2 Description

In the insulation systems the VIPs are considered to form a discontinuous, flexible network, where the layers of panels are staggered (Figure 55). The groove and ridge edges on the panels (shown in Figure 55 only on two lateral sides, but applicable to all four lateral sides of the panel) secure alignment of the panels while allowing contraction and relative movement (panels are allowed to move along grooves).

3.22.3 Advantages

- Allows relative movement of panels (e.g., thermal expansion, sliding), while preventing them to completely misalign (staggered layers are maintained)
- Decreases thermal bridges by increasing tortuosity of the heat transfer path
- Does not prevent sweeping gas among panels (purging the interstices among panels of undesired gases)

3.22.4 Disadvantages

- Higher manufacturing cost
- Need to check integrity for vacuum load from panel

3.23 Supports and connections SC_02

Support name:	Structural support of the tank – Load bearing inner wall
Concept ID:	SC_02

3.23.1 Sketch

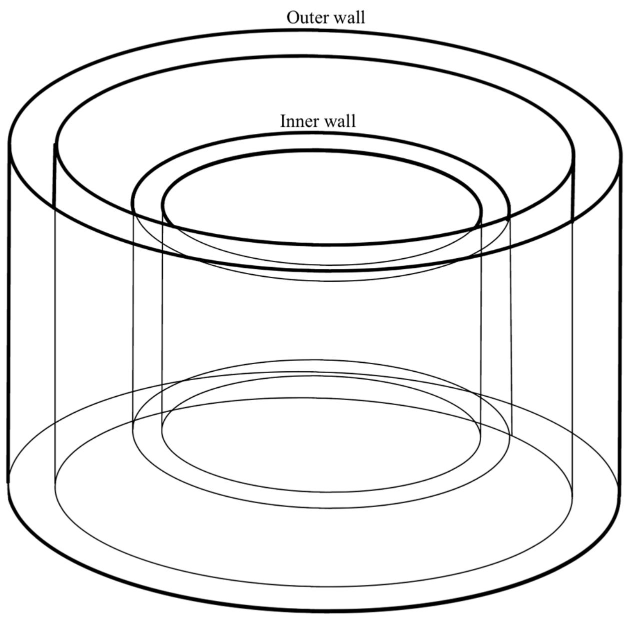

Figure 56: Tank schematics in the case of a single insulation layer and the cylindrical onshore proposed shape (SC 02)

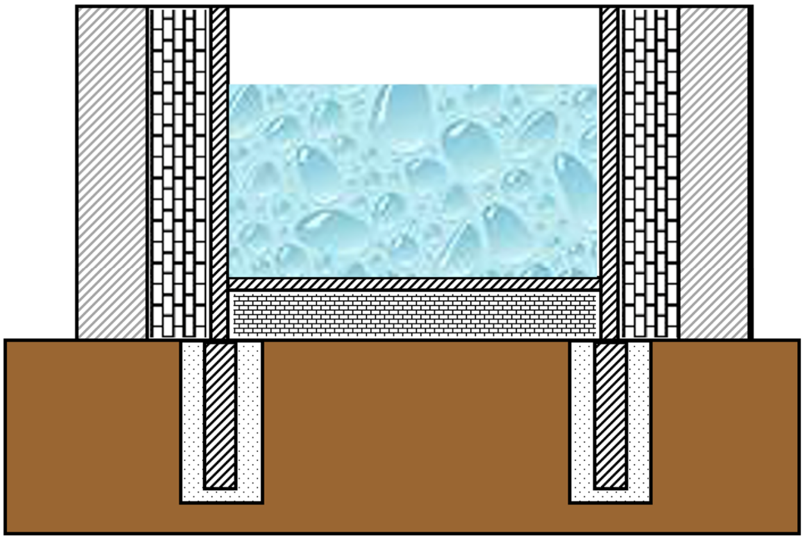

Figure 57: Tank schematics where, for the cylindrical onshore option, support legs are sketched for the inner cylinder, with their corresponding insulation technology (SC 02)

3.23.2 Description

Tank is made of two shells: an inner wall (material suitable for LH_2 contact) and an outer wall (material not necessarily suitable for prolonged LH_2 contact, but “resilient” in case of accidental contact).

In this concept the inner wall is designed to bear load: a) its own-weight (inner roof may be supported by external roof by rods), b) hydrostatic pressure of LH_2, c) pressure/vacuum in gap, d) pressure in LH_2 storage (expected to be near zero in the system analysed), e) other accidental loads (e.g., earthquake).

The outer wall is designed to bear load: a) its own-weight, b) outer roof (and inner roof if supported by rods), c) pressure/vacuum in gap, d) other accidental loads (e.g., earthquake, snow, wind).

The internal structure is supported by rods and columns, so that in this concept the insulation is not load-bearing. Support to lateral loads is provided by angled rods in the horizontal plane for transferring lateral loads to external supports and for keeping the inner and outer walls concentric (the rods are accommodated through the VIPs which are designed with appropriately angled slots). Vertical loads are borne by a bottom annulus and columns (Figure 57 shows a detail of how insulation continues around the columns).

3.23.3 Advantages

- Allows required containment
- Independent construction of external and internal wall
- VIP shall be designed with load bearing characteristics only for own weight and the one of the connected stack (see NIC_14)
- Gap between walls can be oversized to allow access for inspection (e.g., by remote controlled robots)

3.23.4 Disadvantages

- Higher thermal inertia of inner wall
- Larger quantity of LH_2 compatible alloy

3.24 Supports and connections SC_03

Support name:	Structural support of the tank – Load bearing outer wall
Concept ID:	SC_03

3.24.1 Description

Tank is made of two shells: an inner wall (material suitable for LH_2 contact) and an outer wall (material not necessarily suitable for prolonged LH_2 contact, but “resilient” in case of accidental contact).

The outer wall is designed to bear all the loads: a) its own-weight (and roof if not supported otherwise), b) hydrostatic pressure of LH_2, c) pressure/vacuum in gap, d) pressure in LH_2 storage (expected to be near zero in the system analysed), e) other accidental loads (e.g., earthquake, wind, snow, etc.).

The inner wall is a thin membrane (corrugated to allow for thermal expansion) supported by the VIP stack according to the hanging method described in NIC_16.

3.24.2 Advantages

- Allows required containment
- Low thermal inertia of inner wall
- Lower quantity of LH_2 compatible alloy

3.24.3 Disadvantages

- VIP shall be designed with load bearing characteristics (own weight, weight of stack, but also loads from LH_2)
- Non-independent construction of inner and outer walls

3.25 Supports and connections SC_04

Support name:	Load bearing panel hanging system
Concept ID:	SC_04

3.25.1 Sketch

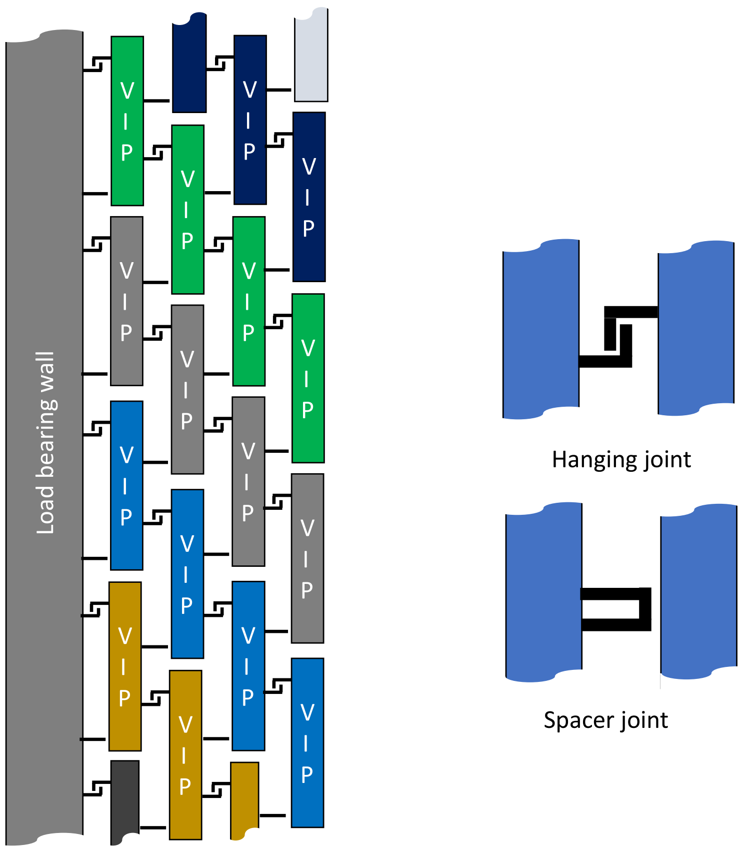

Figure 58: Detail of a section of a single-layer insulation with connection system keeping the panels in place during operation. VIPs with the same color are mutually bearing vertical loads (SC 03)

3.25.2 Description

The panels hang on rails connected to the load bearing wall (in configuration NIC_16 the same system holds the internal membrane wall or a framework supporting the internal membrane wall). Hanging is provided by an L shaped rail; another spacer, allowing free sliding, keeps layers even.

As visible in Figure 58, each panel holds its own weight and the one of the staggered panels attached to it; the weight of the staggered stack right above or below is not borne by the panel.

3.25.3 Advantages

- Keeps VIPs in place
- VIPs at the bottom of a vertical wall do not bear all the load of the VIPs above
- Contraction from cooling is spread homogeneously among all the gaps between the panels (no vertical displacement of the top of the VIPs pile occurs)

3.25.4 Disadvantages

- Introduces some space among panels (may be filled by a spacer), creating extra volume for the sweeping gas

4 Promising insulation concept

Analyzing the advantages and disadvantages of the individual concepts presented in this document, a promising insulation concept as shown in Figure 59 based on a double wall that is divided into two chambers by a gas tight barrier. In this concept the chamber next to the LH2 storage will be named inner insulation chamber, and the chamber close to the environment will be named outer insulation chamber. The barrier could be a membrane or wall, that can be equipped with pipes that enables to support the wall by nitrogen (LN2). LN2 is an economic fluid for precooling and cooling the insulation in general and to avoid losses by boil-off from LH2. Furthermore, the LN2 can be used to ensure temperatures in the outer insulation layer above the boiling temperature of the system gas applied in the outer insulation layer. By this condensation and freezing of system gas is avoided.

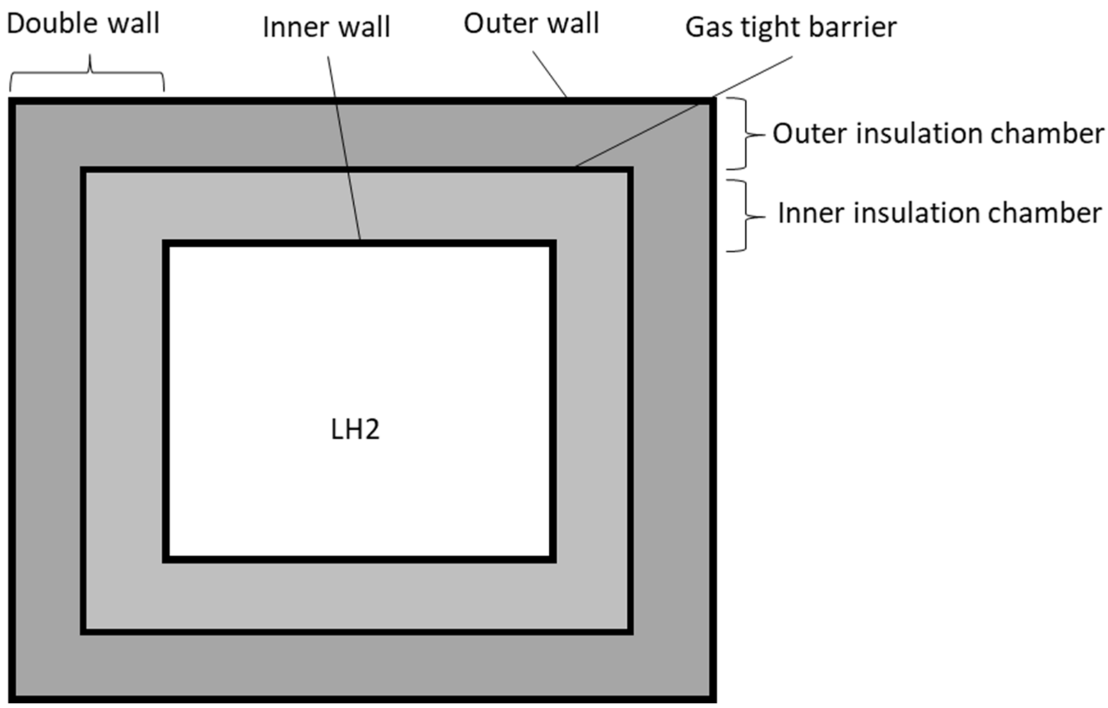

Figure 59: Schematic of LH2 Tank based on a double and a gas tight barrier

Within the chambers vacuum insulation panels (VIPs) are promising thermal insulation elements. VIP consists of a rigid, highly porous core material enclosed within a gas-impermeable barrier envelope, which is subsequently evacuated and gas-tight sealed. Typical core materials include conventional insulation materials with low thermal conductivity, while the envelope typically comprises aluminum or metalized multi-layer films. Additionally, getters are incorporated to absorb residual gases or vapor within the sealed enclosure and increase the friction between the envelope and the core material. This configuration effectively suppresses conductive, convective, and radiative heat transfer, resulting in exceptionally low thermal conductivities that are contingent on both the core material and the vacuum level. The envelope is gas-tight, which can be realized by thin metal foils or metalized plastic foils. These materials enable to guarantee to achieve the required quantity of vacuum about 25 to 50 years, which is necessary to achieve the required insulation performance. By this structure a VIP is functionally similar to the double wall in a conventional LH_2 tank. The filling material serves as a thermal insulation and support core, which ensures that the envelope does not deform significantly when the vacuum is drawn. It also absorbs shear forces between the envelope and core material, providing a dimensionally stable structure and makes the VIP mechanically stiff. While the VIP core forms a thermal superinsulation, the envelope exhibits a significantly higher thermal conductivity. The thermal bridging effect of the envelope can be minimized by arranging VIPs in staggered stacks and using envelope materials with the lowest possible thermal conductivity. In addition, the materials must withstand cryogenic temperatures down to -253°C. Furthermore, components of the insulation that may be exposed to temperatures below the boiling points of oxygen and nitrogen must be protected from air. illustrates the schematic of a VIP.

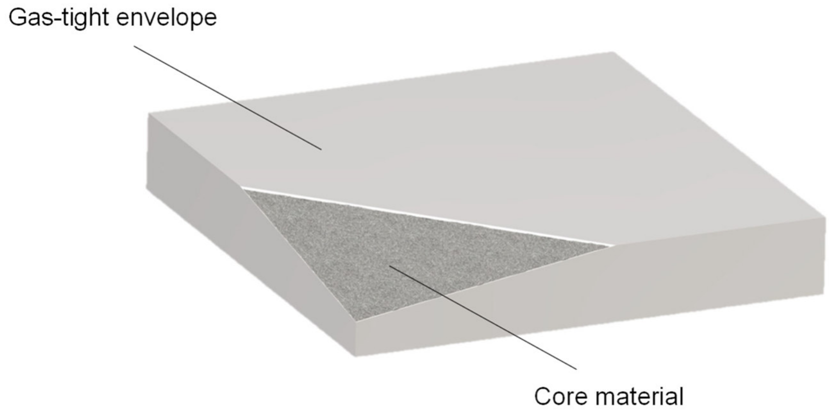

Figure 60: Schematic of a vacuum insulation panel

The inner insulation is between the gas tight barrier of the double wall and the inner tank wall. The first insulation layer is equipped with either VIPs (as in Figure 61a) or a low-conductivity filling material (as in Figure 61b). Across this layer, the temperature ranges from –253 °C (i.e., the temperature of the inner tank wall) to –196 °C (i.e., the liquefaction temperature of nitrogen at ambient pressure). The VIPs or porous materials are positioned in a gaseous hydrogen or helium atmosphere to prevent air condensation and freezing. On the one hand, gaseous hydrogen is easily available from the boil-off of the stored LH_2 and does not require high-performance sealings between the tank and the inner insulation. On the other hand, when using helium, the inner insulation layer must be gastight to prevent the formation of a helium-hydrogen mixture. The latter must be under a slight overpressure to avoid the gas ingress from the outer to the inner insulation (a few Pa are sufficient).

The outer insulation layer is located between the gas tight barrier of the double wall and the tank's outer wall, followed by the environment. Temperatures range from –196 °C to ambient temperature. This means a gas with a low boiling point, preferably nitrogen, can be present in the outer insulation layer. The selection of the gas depends on the temperature of the cooling fluid of the gas tight barrier of the double wall. The latter must be under a slight overpressure to prevent the transfer of gases from the environment into the outer insulation layer (a few Pa are sufficient). VIPs in both variants ensure thermal insulation in the outer layer (see Figure 61a and Figure 61b). An external wall separates the insulation system from the environment. It serves as a protective tank for any leakage from the inner tank, as is also common for LNG tanks [9]–[13].

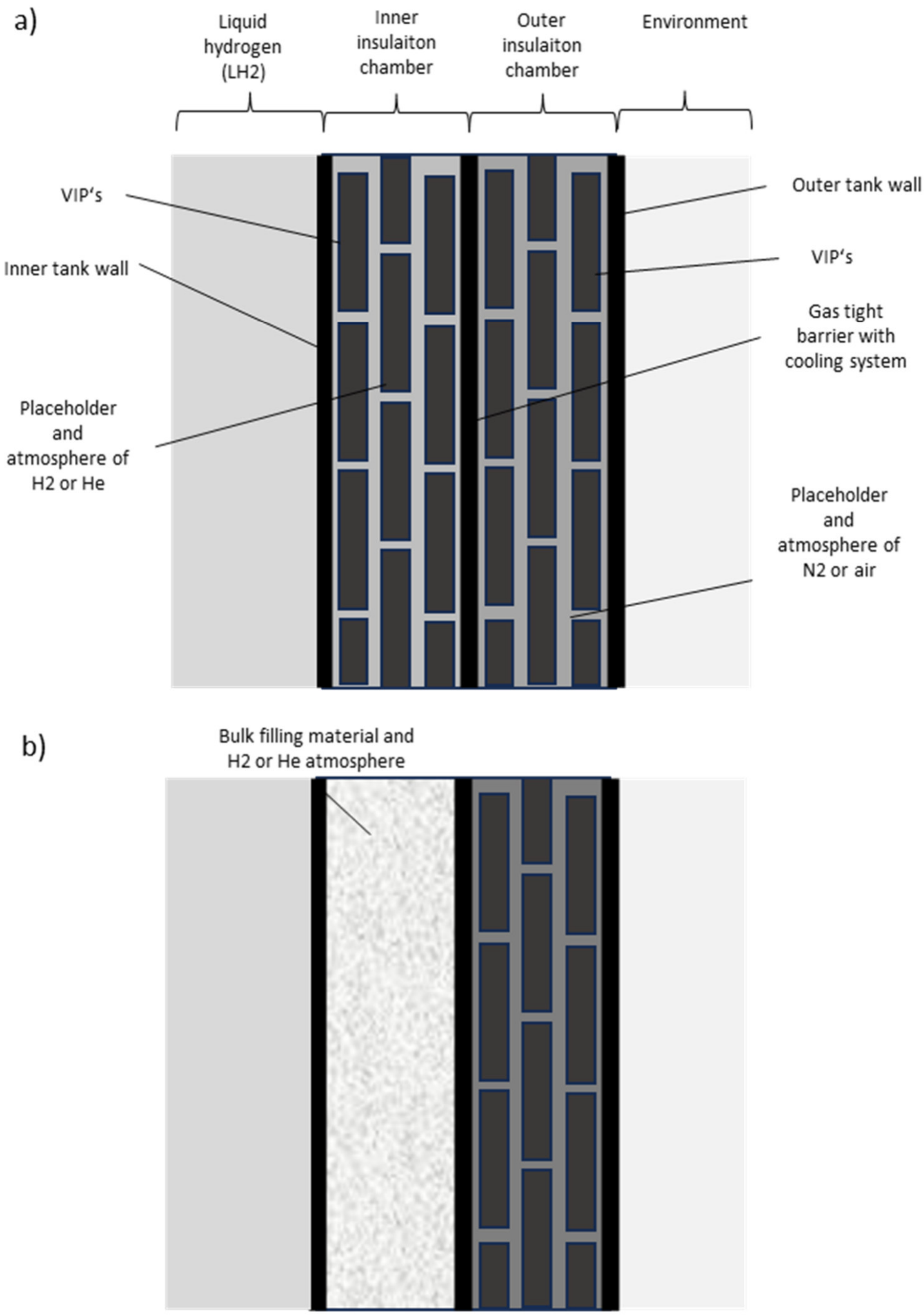

Figure 61: Thermal insulation for efficient and safe storage of liquid hydrogen. a) Configuration with two layers of VIPs. b) Configuration with porous filling material and VIPs

4.1 VIP arrangements and connections

A crucial aspect of the insulation system is the arrangement of VIPs. Various methods can be used in the inner and outer insulation chamber, depending also on the position within the insulation system (e.g., vertical walls, roofs, ceiling area, etc.), the shape of the tank (e.g., cylindrical, prismatic, etc.), and the field of application (e.g., maritime or stationary). In general, two main methods can be distinguished:

- Form-fit VIPs
- Suspended VIPs

With the form-fit method, the position of the VIPs in relation to each other is maintained by interlocking them thanks to their geometrie. This can be done using tabs in one direction (in Figure 62a) or in two directions (in Figure 62b), by using different VIP sizes (in Figure 62c), or by offsetting the VIPs (in Figure 62d). These methods are potentially suitable for thermal insulation of floors, ceilings, and walls.

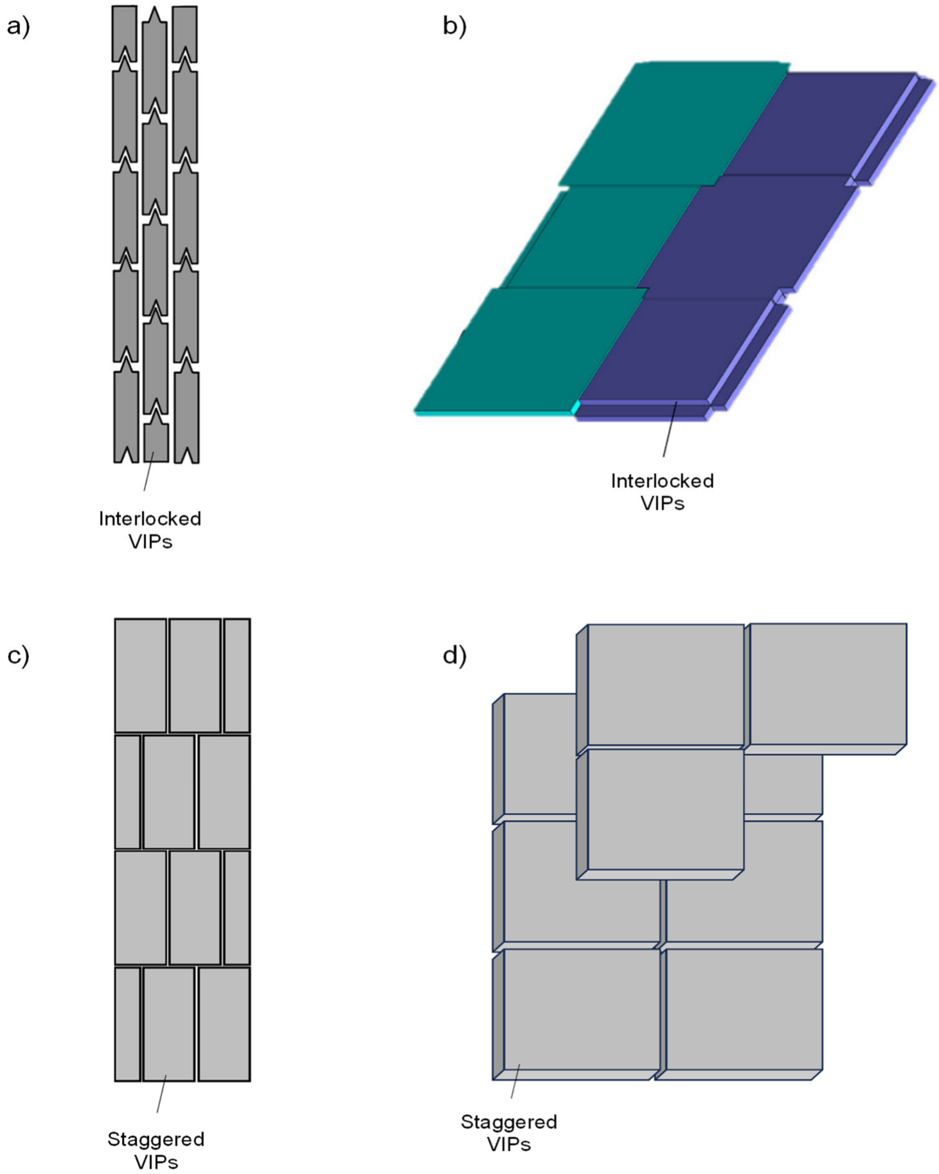

Figure 62: a) Interlocking VIPs with one-directional tabs. b) Interlocking VIPs with two-directional tabs. c) Staggered VIPs with different sizes. d) Staggered and overlapped VIPs

The suspended methods are based on additional elements that hold the VIPs in position. Load-bearing structures with hooks and spacers can be used, as shown in Figure 63a,

Figure 63b, and Figure 63c.

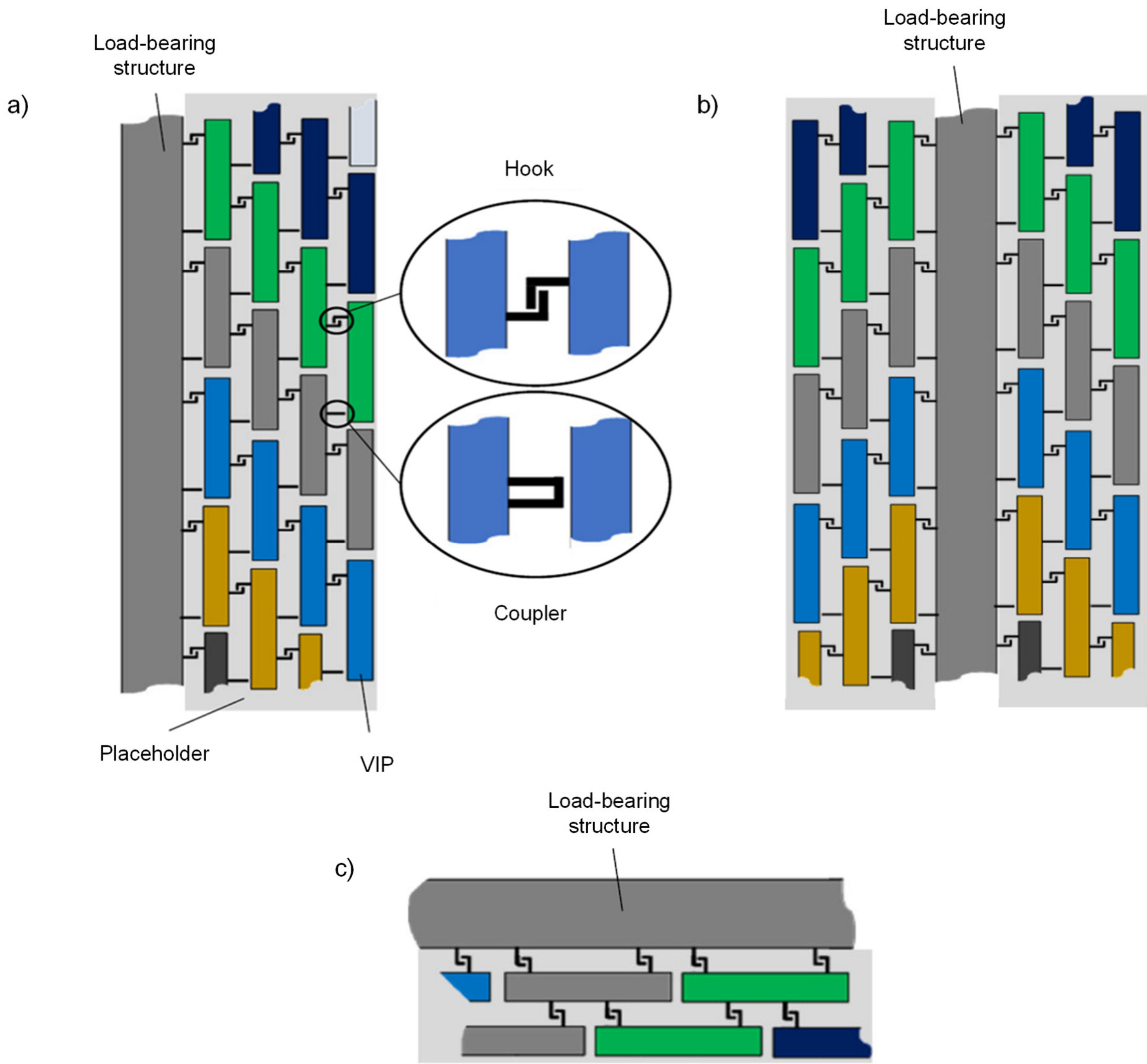

Figure 63: Suspended VIPs with hooks and spacers. a) Inner insulation layer anchored to the inner tank wall. b) Separation wall bearing inner and outer insulation layers. c) Outer roof bearing the insulation system

Alternatively, ropes with holding devices and rope clamps can used for floors, as shown in Figure 64a, and roofs, as shown in Figure 64b. Although generally applicable to the entire insulation system, these methods are particularly suitable for vertical walls. The suspension methods allow the use of very large VIPs and pre-assembled insulation modules, which can then be embedded as a package in the inner and outer insulation layers. The suspension method does not offer the same service options as in the vertical walls in the ceiling area.

Clamps can also be used to connect the VIPs located in vertical walls and ceilings, as shown in Figure 65a and Figure 65b. This solution allows for pre-assembled VIP modules to be easily positioned between the two tank walls. In principle, a combination of form-fit and suspension methods is also possible. Placeholders must be positioned between the VIPs to limit the contact between the VIP envelopes as well as to reduce gravimetric gas flows and so to prevent heat transfer by convection. Spacers can be, for example, sheets made of glass fibers or foams. Placeholders can be inserted during installation or be part of a VIP.

Furthermore, bars can be used to connect the VIPs located in vertical walls and ceilings, as shown in Figure 66a and Figure 66b. This solution allows for pre-assembled VIP modules to be easily positioned between the two tank walls. To apply this method VIPs with and without holes could be suitable. For last one clamps can be used. As for the previous methods placeholders could be positioned between the VIPs to limit the contact between the VIP envelopes as well as to reduce gravimetric gas flows and so to prevent heat transfer by convection. Spacers can be, for example, sheets made of glass fibers or foams. Placeholders can be inserted during installation or be part of a VIP.

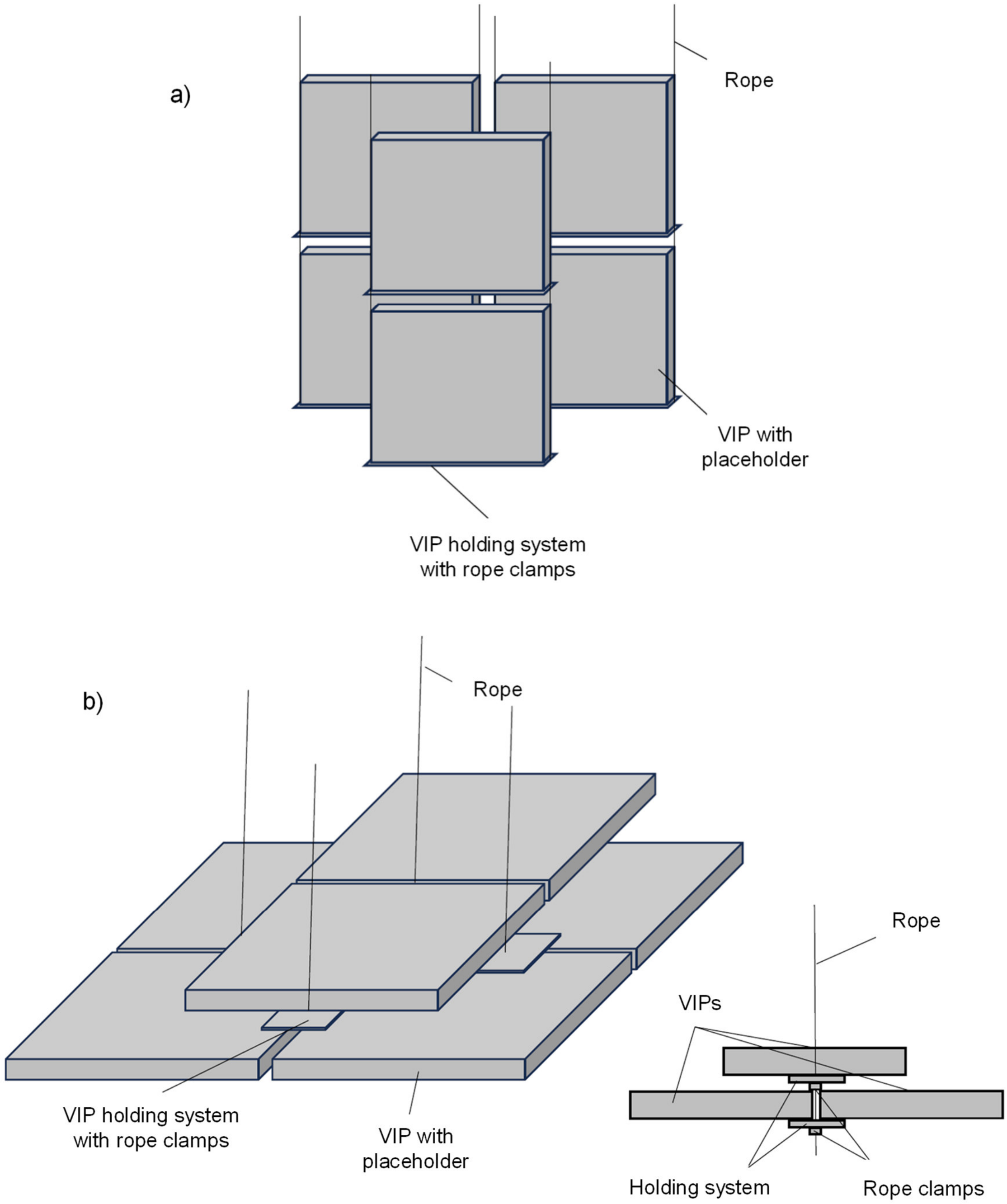

Figure 64: Suspension method with ropes and holding devices for VIPs positioned in a) vertical walls and b) roofs

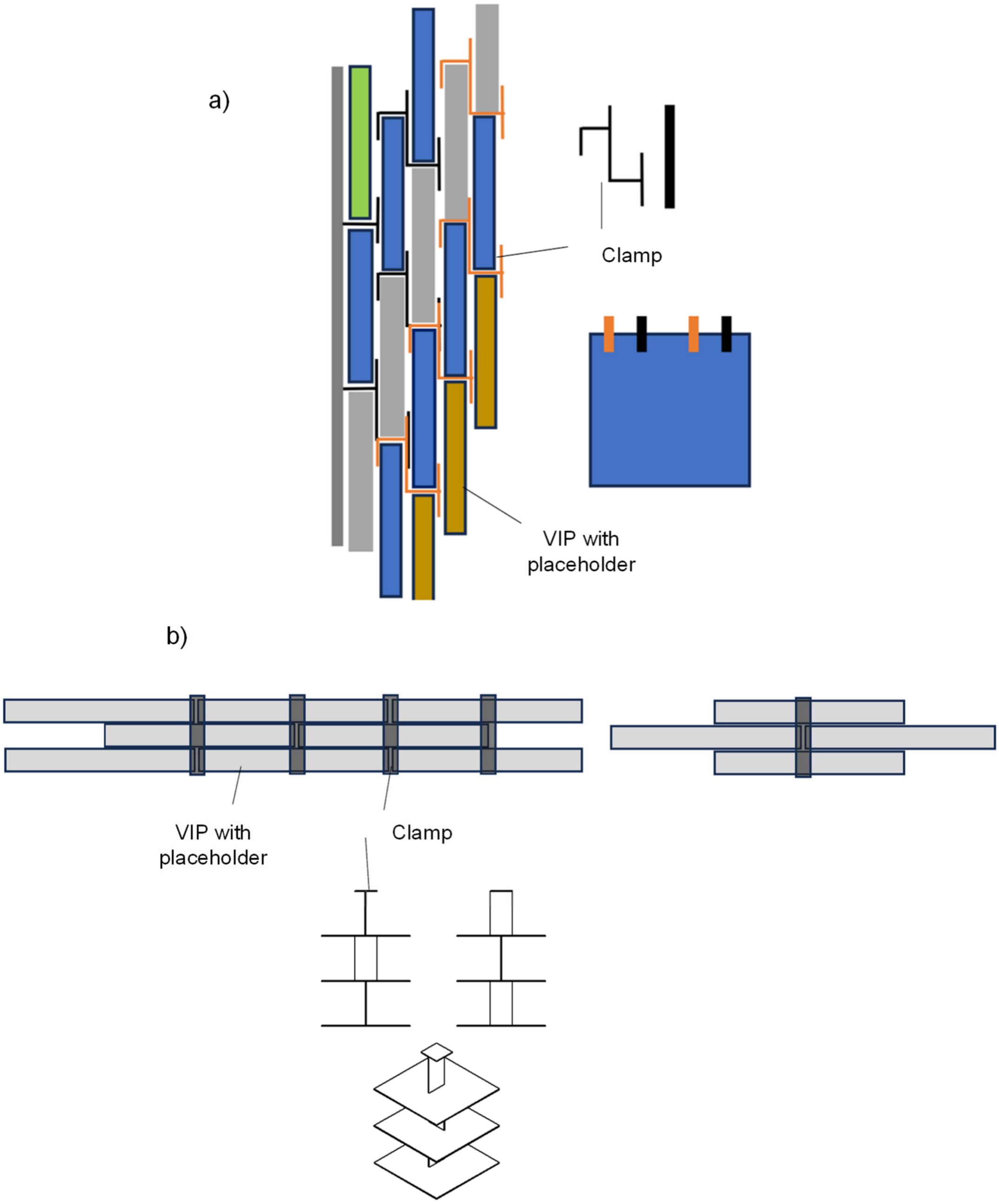

Figure 65: Suspension method with clamps for VIPs positioned in a) vertical walls and b) roofs

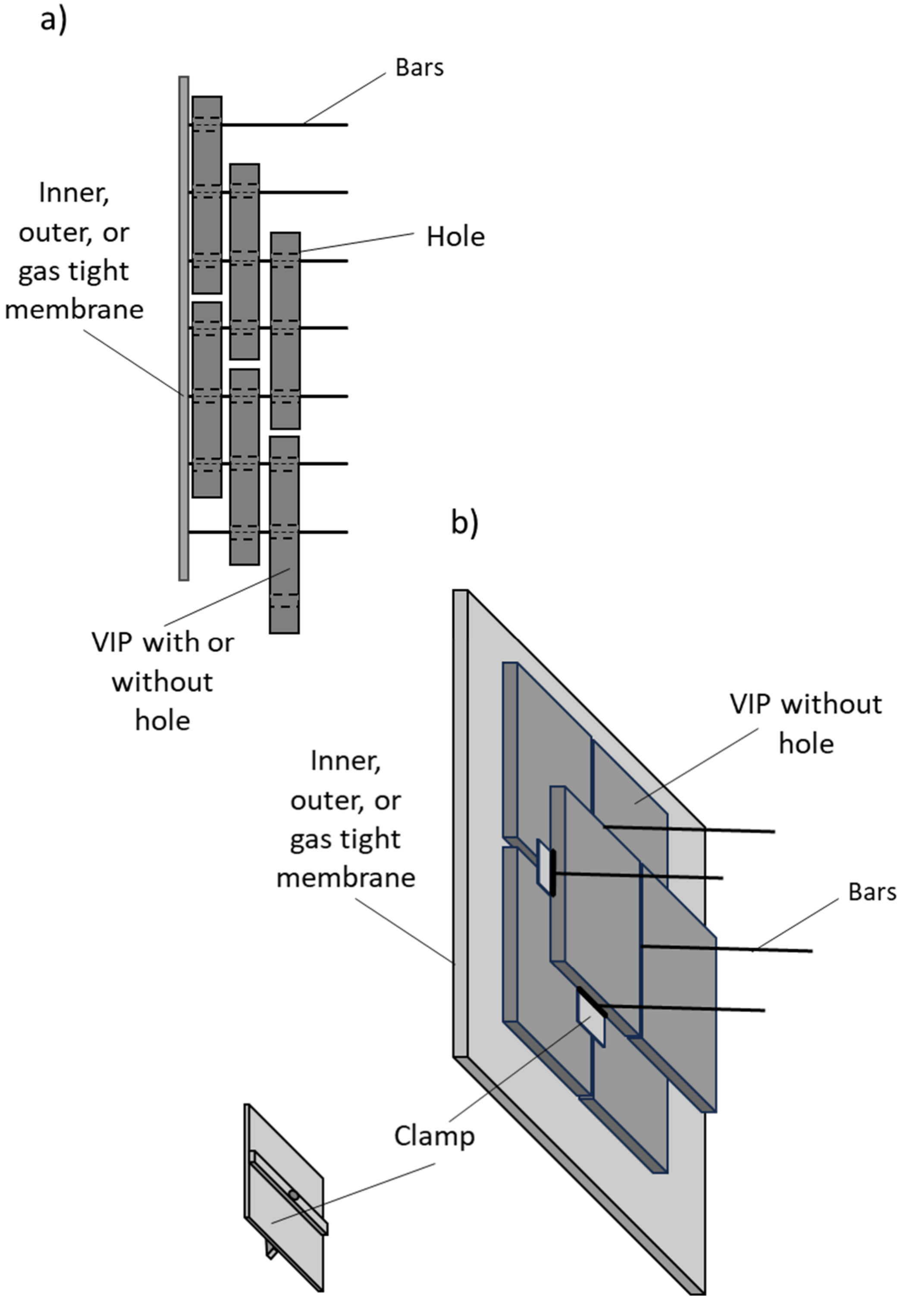

Figure 66: Suspension method with bars for VIPs positioned in a) vertical walls and b) roofs

4.2 Key features

The main characteristics and the inherent benefits of the novel insulation concept can be summarized as follows:

- The outer and inner insulation chamber form together the thermal insulation of the tank. These are divided by a gas tight barrier, i.e., a membrane or wall made of stainless steel (preferably AISI 316 L, alternatively AISI 304 L) with a thickness ranging from 0.05 mm to 50 mm. The gas tight barrier is cooled with liquid nitrogen so that it always has a higher temperature than the boiling point of the gas in the outer insulation layer. In addition, temperature control can be used to cool down the insulation, significantly increasing the system's efficiency and minimizing boil-off during filling operations.
- Stacked vacuum insulation panels provide thermal insulation. These can have different standard sizes and be produced in large quantities with consistent quality control. The envelope of the VIPs in the inner insulation layer should be made of AISI 316 L or AISI 304 L foils with a thickness from 0.05 mm to 0.2 mm. This makes them sufficiently tight for a hydrogen or helium environment. In addition, it guarantees sufficient resistance to thermo-mechanical stresses at temperatures down to –253 °C. The envelopes of the VIPs in the outer insulation layers can also be made of multi-layer, metalized plastic films (similarly to the VIPs commonly used in the building industry). Various porous materials, such as different types of perlites, fumed silica, or fibers, and hollow glass microspheres are suitable core materials for the VIPs. Small pore sizes, combined with the envelope vacuum, reduce heat flows through convection, heat conduction, and radiation. Typical pressures within the VIPs range from 1 to 100 Pa. The dimensions of the VIP can vary from $0.5 \times 0.5 \times 0.05$ m³ to $16 \times 3 \times 0.5$ m³. The shape of the VIPs is not necessarily a parallelepiped. Other shapes are also possible and can be employed to ensure thermal insulation of corners or pipes.
- VIPs under optimal conditions exhibit a thermal conductivity approximately 10 times lower than rock wool, glass wool, aerogels, and polyurethane foams. The low thermal conductivity results from the combination of the thermal conductivities of the filling material and the envelope. The latter has significantly higher thermal conductivities than the filling material and, therefore, represents a thermal bridge that needs to be reduced. Large VIPs can minimize this thermal bridging effect. In addition, appropriate positioning of the VIPs can further reduce heat transfer. For this purpose, they should be staggered. The size and positioning of VIPs can enable them to reach an average thermal conductivity of 4 mW/(m·K). This thermal conductivity is significantly lower than insulation materials used in large-scale LNG storage, which typically ranges between 20 and 45 mW/(m·K). Substituting air with hydrogen or helium eliminates the risk of oxygen and nitrogen condensation and freezing. However, it would increase the thermal conductivity by a factor of three (due to the higher heat transfer coefficients of helium and hydrogen). As a result, the novel insulation system can provide a level of insulation comparable with conventional double-walled LH_2 storage tanks, which are longer to produce, less flexible in shapes and geometries, and not tolerant to multiple faults. The total thickness of the insulation is at least 0.5 m. Greater wall thicknesses of 1 to 2 m are desirable, as they enable more efficient and service-friendly installation methods for VIPs. Larger wall thicknesses are also possible to integrate the system into existing tank systems.
- The proposed insulation system allows the modular manufacturing of stationary and maritime tanks. Standard prismatic VIPs require the adoption of prismatic tanks.

However, VIPs can also be arranged prismatically using suspended support structures to fit different tank shapes.

- The novel insulation system makes it possible to reduce the production time of the tank by parallelizing the production of VIPs while increasing quality control in industrial environments.
- The VIP-based insulation, divided into inner and outer layers, is durable and highly efficient. This prevents the formation of condensation and ice of various gases, which could directly damage the envelopes of the VIPs and minimizes the risk of explosions due to the formation of oxygen-enriched atmospheres. Furthermore, the risk of vacuum loss in one or more VIPs is tolerable, maintenance intervals become predictable, and the total loss of the stored LH_2 does not accompany faults in the insulation. As a result, safety systems are cheaper and less complex, thus impacting the overall investment cost to build the storage tank.

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