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From Machine Enclosure to Pressurised Build Chamber

Enabling Additive Manufacturing of Large Components in Inert Environments

EVELINA KARLSSON
ANTON WIKSTRÖM

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

Chalmers University of Technology
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Supervisor: David Stomilovic, Permanova Lasersystem AB
Examiner: Ola Isaksson, Department of Industrial and Materials Science

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Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Abstract

Additive manufacturing (AM) of large titanium components for the aerospace industry requires inert environments to prevent oxidation and contamination to ensure material integrity. As the aerospace manufacturers scale up titanium AM, maintaining these inert atmospheres becomes increasingly challenging. Permanova Lasersystem AB is developing a scaled up laser directed energy deposition (L-DED) system with a larger and reversible build plate to enable larger and more efficient builds and improved residual stress control. However, the current tent-based inert enclosure cannot be expanded to work with the new build plate. This thesis explores how the existing laser safety enclosure surrounding the system can be adapted to also function as an overpressurised inert enclosure by assessing what overpressure it should withstand and maintain, how it responds to it, what the biggest problems for maintaining it are, and how different solutions for solving those problems compare. Interviews, standards review and state-of-the-art analysis established that a pressure differential of 50 Pa prevents ambient air infiltration; therefore, 100 Pa was selected as the design pressure to incorporate a safety factor of two and maintain recommended engineering margins.

Leakage assessment revealed critical leakage paths at the floor interface, ceiling, corners, and panel joints, while structural simulations identified weaknesses in the active protection panels and part of the skeleton. Based on these findings, sealing and reinforcement concepts were developed and evaluated. The final solution was to implement metal plates and L-profiles together with a polyurethane sealant for covering the major leakage paths, a fully sealed active panel to not only prevent leakage but also to increase stiffness and an additional roof beam to eliminate deflection. The results demonstrate that the existing laser enclosure can effectively be adapted into a large, overpressurised inert enclosure without extensive redesign.

Keywords: overpressure, additive manufacturing, sealing, machine enclosure.

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Evelina Karlsson & Anton Wikström
Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AFS	Swedish Work Environment Authority regulations (Arbetsmiljöverkets författningssamling)
AM	Additive Manufacturing
BOM	Bill of Materials
CAD	Computer Aided Design
EPDM	Ethylene Propylene Diene Monomer
HVAC	Heating, Ventilation, and Air Conditioning
ISO	International Organization for Standardization
L-DED	Laser Directed Energy Deposition
LPM	Litre Per Minute
Pa	Pascal
PBF	Powder Bed Fusion
PPM	Parts per Million
SMX	Soudal Modified Extensions
TPE	Thermoplastic Elastomer

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1

Introduction

In this chapter, the background and context of the thesis are outlined, providing the foundation necessary to understand the problem under investigation. The problem statement is presented together with the motivations for the study and its objectives. Furthermore, the scope and limitations of the thesis are defined to clarify the boundaries within which the thesis has been conducted.

1.1 Background

The use of additive manufacturing (AM) solutions to produce metal products has increased significantly in recent years within industries such as automotive, aerospace, and medtech, due to lower energy consumption, shorter lead times, and improved material efficiency (RISE, 2025, 2026). There are some different types of AM solutions for metal, such as laser directed energy deposition (L-DED), powder bed fusion (PBF), and binder jetting, where L-DED is the one most suitable to make big builds and complex geometries due to more degrees of freedom (Tan et al., 2022).

Permanova Lasersystem AB, which since 2022 has been a part of GKN Aerospace, manufactures and installs AM solutions to the aerospace industry, an industry that has been a pioneer in additive manufacturing and continues to push the boundaries of the technology, especially by developing methods to produce increasingly more complex, larger, and higher-performance components (European Patent Office, 2023; GE Aerospace, 2022). However, as component size and or number of components increases, so do the residual stresses arising from localised thermal cycling, and warping of the build plate becomes increasingly difficult to mitigate (Cao et al., 2016). To address this, Permanova is developing a system that incorporates a build plate with not only more than twice the build area, but also a turntable that can flip it, enabling symmetric material deposition on the opposite side. This configuration is intended to equilibrate residual stresses and thereby reduce or prevent warping, while simultaneously doubling the effective build area and consequently decreasing the number of process setups.

When producing components for the aerospace industry, titanium is a common material choice due to its high strength, low weight, and excellent temperature resistance (Chen et al., 2022). Titanium will, however, react with atmospheric gases at elevated temperatures, forming a brittle oxide layer that degrades its mechanical properties, particularly ductility and fatigue resistance (Chen et al., 2022). The industry's strict requirements on purity and material integrity mean that the titanium must be carefully protected from contamination during processing. To prevent this, processes such as AM, melting, and heat treatment are carried out in oxygen-deficient environments, such as vacuum or inert gas atmospheres, using argon or helium (Chen et al., 2022).

While local shielding gas nozzles are often used in L-DED, achieving the strict atmosphere purity required for large-scale titanium components remains a significant challenge (Chen et al., 2022). To enable the production of larger build volumes without compromising material integrity, there is a need for specialised environmental containment, such as large-scale inert gas chambers.

1.2 Aim

The aim of this project is to develop concepts that adapt Permanova's encapsulated production cell containment into an overpressurised build chamber suitable for additive manufacturing to accommodate a significantly larger build volume.

1.3 Objectives

To achieve the aim, the project focuses on ensuring the structural and inert integrity of the enclosure. This involves a systematic evaluation of pressure dynamics, leakage risks, and sealing solutions. To achieve this, the following objectives have been defined:

- Identify what poses a risk of air leakage into the enclosure.
- Evaluate the structural load from overpressurisation.
- Identify and evaluate potential solutions for sealing and reinforcing the enclosure.
- Evaluate effects on passive and active protection panels from overpressurisation.
- Identify and evaluate potential solutions for leakage free active protection panels.

1.4 Scope and Limitations

The project is limited to one academic semester, approximately 20 weeks. This defines a strict time frame and requires a detailed project plan at the outset to determine what can realistically be achieved and how activities should be prioritised. To ensure a feasible scope within this time frame, certain subsystems of the enclosure, such as design and sealing of the door and the cable feedthroughs, are excluded from the project. Additional constraints arise from the requirement that the enclosure must be compatible with Permanova's existing machinery and operate reliably in an argon-filled environment.

Another limitation concerns the available resources at Permanova and Chalmers University of Technology for prototyping and testing. This includes both physical testing capabilities and access to software tools for digital prototyping, such as computer aided design (CAD) and simulation programs. The project is therefore influenced by the tools, facilities, and support that are practically accessible during the thesis period.

2

Methods

This chapter outlines the methods used in each phase of the project. Structuring the work into separate phases provided clarity and increased the likelihood of a successful project. The phases and their corresponding methods are arranged as follows: preliminary study, system requirements, evaluation of today's solution, concept development, and verification of the solution.

2.1 Preliminary Study

A preliminary study was conducted to establish an understanding of the problem, relevant technical areas, and potential solution approaches. The study was divided into several phases, beginning with interviews, followed by a state-of-the-art analysis including patent and technical analyses. Finally, today's solution was examined in detail with respect to its design and functionality.

2.1.1 Interviews

To capture knowledge that is difficult to obtain from written sources, particularly concerning practical experiences, semi-structured interviews were conducted with the primary stakeholder and relevant industry practitioners. The interviews were structured around open-ended questions based on findings from the preceding literature review. The semi-structured approach was specifically chosen for its adaptability, allowing the conversation to evolve naturally and incorporate unforeseen insights or tangential topics that emerged during the dialogue (Bryman, 2018).

In total, four semi-structured interviews were conducted: one with the primary stakeholder, Permanova, one with a supplier of passive panels to Permanova, one with a company specialising in cleanroom construction, and one with a cleanroom manager. These interviews aimed to complement the technical analysis by providing context-specific understanding and reducing the risk of overlooking implicit requirements. The insights gained were used to qualitatively shape the development process and support decision-making. To maintain continuous alignment with company needs throughout the project, additional unstructured interviews and informal discussions were also held with Permanova representatives.

All semi-structured interviews were audio-recorded and subsequently transcribed to ensure accuracy. Field notes were taken during each interview to complement the recordings. The recordings were deleted after transcription had been completed.

Other relevant stakeholders, such as assemblers and the parent company, were identified but not directly involved due to limited access and time constraints. Their perspectives were instead considered indirectly through the primary stakeholder and supplementary sources.

2.1.2 Review of Existing Solutions

To gain a better overview of similar solutions available on the market, a review of existing solutions was conducted. Relevant solutions were identified through structured searches in scientific databases, company websites, and technical reports using keywords related to the relevant technical areas.

2.1.3 Patent Analysis

A patent search was conducted on Espacenet with a focus on relevant technical areas. The aim was to establish a state-of-the-art overview and to identify technical solutions that could serve as inspiration in the concept development phase. The search was thus used primarily to broaden the technical reference space and to capture less conventional solution principles that otherwise risk being overlooked.

2.1.4 Technical Analysis

To further develop an understanding of the system, a technical analysis was conducted. This involved reviewing relevant standards and applying equations for key parameters that affect system performance. The analysis provided a foundation for evaluating solutions and identifying critical factors influencing the development of a solution.

2.2 System Requirements

After the necessary background information had been collected, it was structured and used as a basis for developing potential solutions to the problem. This was first done by decomposing the system into a functional tree to achieve a clear overview of its main functions and subsystems.

Subsequently, all requirements and wishes were structured into a requirements specification, which served as the foundation for the subsequent development phase.

2.2.1 Functional Analysis

To gain a clearer understanding of the overall system, a functional analysis was conducted. A hierarchical function tree was developed, with the main system function at the top level. This was subsequently decomposed into sub-functions, which were further broken down until all relevant system functions were identified. The scope of this thesis was then highlighted within the function tree. This approach ensured that all relevant functions were considered during the project.

2.2.2 Requirement Specification

Based on the information and knowledge gathered during the preliminary study phase, a requirements specification was developed. The specification systematically documented all identified requirements and desired characteristics. For each criterion, the following information was defined: name, description, importance, value, unit, verification method, and source. This structure ensured traceability, clarity, and measurability throughout the complete process.

The value specifies the level required for a criterion to be considered fulfilled. Importance was assigned only to desired characteristics and rated on a scale from 1 to 5, where 5 represented the highest importance for meeting customer expectations.

The requirements specification was treated as a living document and served as a guideline throughout the project, forming the basis for design decisions and concept evaluation. As the project progressed, new criteria could be added as they were identified, and existing criteria were revised or removed if they were no longer considered relevant.

2.3 Evaluation of Today's Solution

Since the aim of the project was to adapt the design to work as a suitable AM build chamber for larger build volumes, not everything had to be improved. Therefore, an initial evaluation of today's enclosure was required to state which areas required improvement and which were already sufficient. The evaluation was primarily based on existing CAD models and data sheets to identify components that could pose potential risks to fulfilling the defined requirements. Additionally, several calculations and static simulations were performed to assess whether the existing solution met these criteria.

2.4 Concept Development

Once all groundwork was complete, the process of developing the enclosure components that required improvement began. This was first done by generating concepts, which were then evaluated and screened in order to identify the optimal solutions.

2.4.1 Concept Generation

Based on the areas needing improvement, the project group held brainstorming sessions to generate potential solutions for each problem area. The brainstorming was conducted in an open, non-judgmental manner, in which all ideas were encouraged and documented without immediate evaluation. This approach aimed to promote creativity and ensure a wide range of possible solutions, thereby reducing the risk of overlooking viable alternatives due to early fixation on a specific concept.

Following the brainstorming phase, the identified sub-functions and their respective solutions were structured in morphological matrices to enable systematic combination of the sub-solutions into complete concepts. To avoid generating an excessive number of impractical concepts, incompatible or unrealistic combinations were excluded during the process. Sub-solutions that were not feasible in combination with other elements were removed entirely from further consideration.

2.4.2 Concept Screening and Scoring

To ensure that the most suitable solutions were carried forward in the concept evaluation, the selection was conducted using multiple matrices. These matrices were based on the requirements previously defined for the solution.

2.4.2.1 Elimination Matrix

The concepts generated from the morphological matrix were evaluated using an elimination matrix, in which each concept was assessed against the requirements defined in the requirements specification. Concepts that failed to satisfy any of the mandatory requirements were directly excluded. In cases where compliance was uncertain, the concepts were set aside for further investigation before a final decision was made.

2.4.2.2 Pugh Matrix

The concepts that passed the elimination stage were further evaluated using Pugh matrices. In this method, the concepts were compared against each other based on selected evaluation criteria derived from the requirements specification. Multiple Pugh matrices were constructed using different reference concepts, providing a more robust basis for comparison and supporting informed decision-making.

2.5 Verification of Solution

The final step in ensuring that the solutions met all the specified requirements was to verify their functionality. This was carried out in a similar manner to the evaluation of the existing solution in Section 2.3, using static mechanical simulations. In addition, all component data sheets and the bill of materials (BOM) were reviewed to ensure that the solution complied with and fulfilled the defined requirements.

3
Preliminary Study

To gain a clearer understanding of the problem, a preliminary study was conducted. It began with interviews with relevant stakeholders and industry professionals, followed by a state-of-the-art review. This was succeeded by a technical analysis focusing on overpressure and leak rate. Finally, today's design of the solution was examined in greater detail.

3.1 Interviews

Four interviews were conducted, with the first and most extensive one being with Permanova. The three subsequent interviews were held with a company that offers sealing solutions for applications such as cleanrooms, the supplier of passive panels used by Permanova, and finally, a staff member from the cleanroom facility at Chalmers.

3.1.1 Permanova

The first interview was conducted with Permanova, as they possessed the most comprehensive information regarding today's solution, its limitations, and the goals for the new design. Additional questions were asked to clarify why the problem exists, how it originated, and why it is necessary to fill the entire room with argon. Continuous communication with the company was maintained throughout the project whenever further questions arose or clarifications were needed.

The most critical takeaways from the Permanova interview concerned the enclosure being required to keep an overpressure with an inflow of 283 litre per minute (LPM), hence the maximum leak rate allowed is 283 LPM. Other important insights included a deeper understanding of today's solution, its lifespan, material usage, and the importance of complying with Swedish workplace regulations.

The materials used in today's solution include aluminium for frames, steel for the skeleton and sheets in the active panels, and ethylene propylene diene monomer (EPDM) strips, together with polyurethane sealants, for light-tight sealing. They also provided insight into argon consumption, noting that it is costly and that they aim to use it more efficiently.

3.1.2 Sealant Company

The second interview was conducted with an independent sealing company that designs and assembles sealed enclosures, often for cleanroom applications. This interview was necessary because it was not possible to speak directly with the company responsible for assembling Permanova's enclosure, as the work is typically outsourced to different companies. The interview focused on assembly procedures and on whether their designs incorporate specific measures to withstand overpressure.

The interview made it clear that assembling these enclosures is a demanding process that requires high precision to achieve complete airtightness. However, they do not account for overpressure in their designs, since cleanroom pressure levels are typically very low and do not impose substantial loads on the enclosure. Similar to Permanova, they manufacture their own structural frames but outsource the sandwich panels. In contrast to Permanova, they use a silicone-based sealant, which they consider easier to work with.

3.1.3 Panel Company

The third interview was conducted with the company supplying Permanova with passive panels. They were contacted to obtain a deeper understanding of how the panels function and what alternative solutions they offer. The interview focused on how the panels are affected by overpressure, whether they have completed jobs requiring airtight solutions, and whether they have encountered any issues with their products in pressurised environments.

The main takeaways from this interview were that they have delivered similar solutions, particularly for cold storage facilities and cleanrooms. In these cases, the only adaptation required was the application of additional sealant, as the overpressure involved is too small to pose any structural risk. The sealant they use is an Soudal modified extensions (SMX) hybrid polymer sealant, and they advise against silicone-based sealants due to their lower flexibility.

3.1.4 Cleanroom

A cleanroom facility at Chalmers was contacted to gain insight into the required overpressure and whether any structural issues had been observed as a result. However, the visit did not provide particularly useful information. It became clear that cleanrooms operate with very low overpressure compared to Permanova's system.

3.2 State of the Art

To gain a better understanding of the techniques, products, and methods currently used in relation to overpressure, sealing materials, and other relevant areas, a state-of-the-art analysis was conducted. This included reviewing comparable solutions, examining different sealing materials, and conducting a patent analysis.

3.2.1 Cleanrooms

Cleanrooms maintain extremely low particle and contaminant levels by maintaining strict isolation and cleanliness. This is achieved by controlling airflow direction, ensuring effective air circulation, using filtration, and thereby managing both the sources and the spread of contaminants. Typically, cleanrooms are designed to maintain a clean interior environment by preventing external particles from entering and removing any contaminants generated inside (Standard Tech, 2025).

Part of controlling the flow of air and sources of contaminants is to ensure there are no uncontrolled leaks where contaminants can enter, therefore gaps and seams often have to be sealed. The cleanroom does not have to be completely sealed however, airlocks, cable entryways, ventilation, leaks, etc., are all potential open paths to the other side. To ensure contaminants cannot enter, a differential pressure is typically maintained in all cleanrooms. A differential pressure ensures that, wherever airflow cannot be blocked, it travels only in the preferred direction. The differential pressure can typically be around 7.5-15 Pa in cleanrooms (International Organization for Standardization, 2022), and in some instances, such as Chalmers cleanroom, a pressure ladder is used. This involves an intermediate pressure zone where the pressure is higher than the outside but lower than that of the (inner) cleanroom. In the cleanroom at Chalmers, this works by completely surrounding the cleanroom in two layers of walls, creating an intermediate space which also serves as a recirculation path.

3.2.2 Sealing Materials

Studies of how different industries reduce or prevent leakages through different kinds of seams showed that, almost always, some type of sealing material was used. The most common sealing materials can be divided into four categories: Sealing Strip, Adhesive Tape, Sealants, and Welding.

3.2.2.1 Sealing Strip

Sealing strips are widely used in various sealing applications. They are available in a wide variety of polymer materials, with the most common being thermoplastic elastomer (TPE), EPDM, and silicone (Elasto Proxy, 2024b). They work by being placed between two surfaces, often with an adhesive on one side, and then being compressed during assembly. For proper performance, the strip should be compressed by about 40% of its original height; too little compression can cause gaps, leading to air, water, and dust ingress. However, excessive compression should also be avoided, as it can permanently deform the sealing strip, reducing its ability to recover and increasing the risk of gap formation (Elasto Proxy, 2024a). If properly installed, sealing strips can achieve a long service life, in some cases up to approximately 15-20 years under favourable environmental conditions (Fortex Sealing Systems, n.d.).

Applications: Windows, doors, automotive, heating, ventilation and air conditioner (HVAC), industrial enclosures, and more.

Advantages	**Limitations**
No curing time	Limited performance if incorrectly compressed
Easy to replace	Sensitive to installation tolerances
Long lifespan	Needs clean and even surface
Widely used	Requires compression

3.2.2.2 Adhesive Tape

Three categories of tapes were investigated: conventional sealing tapes, aluminium foil tapes, and double-sided tapes. Conventional sealing and aluminium foil tapes consist of a backing with a single adhesive layer, while double-sided tapes have adhesive on both sides of a carrier. Double-sided tapes are primarily used for joining, whereas the others can also bridge or seal gaps between adjacent surfaces.

Conventional sealing tapes were only briefly considered, as polymer-based tapes were deemed less suitable for the enclosure due to requirements to minimise exposed combustible materials. Double-sided tapes were included despite their primary use in joining applications, as they may still provide partial sealing, although their sealing performance is often unspecified.

The main focus was therefore on aluminium foil tapes, which are widely used in aerospace and automotive applications. They offer high temperature and flame resistance, good mechanical robustness, and fast application (3M, 2024). However, their performance is highly dependent on surface quality, requiring clean and smooth substrates to prevent micro-gaps and edge lifting, which can reduce sealing performance and service life.

Applications: Cable wrapping, joint sealing, corrosion protection, surface protection, thermal shielding, and more.

Advantages	Limitations
Quick application	Requires surface preparation
No curing time	Susceptible to micro-gaps
Removable	Limited service life
Flexible	Edge lifting risk

3.2.2.3 Sealants

Sealants are widely used for a wide range of different types of sealing applications and are available in a wide range of materials. The types mentioned and used by the companies interviewed were silicone, polyurethane, and hybrid polymers, as noted in Section 3.1. Sealants work by being dispensed as a thick substance, which not only fills gaps but also creates an adhesive bond to the surface after curing. For proper performance, consistent bead size and placement are required to avoid gaps or overspill. Additionally, due to chemical exposure risks during handling, sealant application is subject to Swedish Work Environment Authority regulations (AFS) (Swedish Work Environment Authority, 2014).

Sealants are typically elastomeric polymers that maintain the seal even when subjected to movement or deformation, for example, due to thermal expansion or cyclic loads. It also provides resistance to vibration. If properly installed, sealants can achieve a service life of 10-25+ years (GreenSpec, n.d.).

Applications: Construction, windows, automotive, marine, HVAC, industrial enclosures, and more.

Advantages	Limitations
Low outgassing variants	Application quality variability
Adhesive properties	Curing time required
Long service life	Difficult to re-do
Gap filling	Not removable
No seams	Requires compliance with AFS
Flexible	

3.2.2.4 Welding

Welding is a joining process used to permanently bond materials, typically metals, by applying heat, pressure, or both. The process can be performed with or without a filler material, where the filler may be either the same or different from the base materials. Welding creates a continuous joint by either melting the materials together or applying pressure to forge them into a single surface. In addition to joining components, welding can also be used to repair damaged or broken structures (ESAB, 2024).

Welding is classified as “hot work” (heta arbeten), which is regulated through Swedish industry safety requirements and certification systems (Brandskyddsföreningen, 2026). This classification means that at least three people must be involved in the process, and one person must stay to monitor the work as long as there is a risk of fire.

Applications: Permanent joining of metal structures, pressure vessels, pipes, repair work, automotive and aerospace manufacturing, industrial assembly, and more.

Advantages	**Limitations**
Do not need fasteners	Needs to follow AFS regulations
Long lifespan	Permanent solution
Airtight	Risk of defects

3.2.3 Patent Analysis

The patent analysis identified several noteworthy patents related to sealing materials, as well as one dealing with the use of overpressure. Patents relevant to this project are presented in Table 3.1. The patent that contributed the most to this project was ”Pressurized heat exchange ventilation” particularly due to its method of sealing a building through the walls to maintain a pressurised interior. In addition, the adhesive-free centre of the tape inspired new ideas for how tape could be used as the sealing material. The way the patent ”Airtight adhesive tape for doors and windows and window with adhesive tape” uses overpressure to support the sealing strip in becoming more airtight was also an finding that led to the idea that if sealing strips are used, the overpressure should act to assist, not undermine, their performance.

Table 3.1: Relevant Patents

Patent Name	Summary	Reference
Seal Tape	Tape with embedded conductor that signals damage.	(Takeru, 1991)
Water-proof airtight adhesive tape	Elastic butyl tape for airtight sealing around corners and pipes.	(Ishikawa et al., 1991)
Airtight tape for building and its taping method	Tape with a stripe of non adhesive in the middle, designed to accommodate movement at joints and corners.	(Aiyama & Ueki, 2006)
Silicone weather-proof sealant	Ozone-resistant silicone sealant, reinforced with glass fibres.	(Zhiyong & Yaoming, 2020)
System and method for semi-foam flexible sealant with density modifier	Waterborne foam sealant with microspheres that compress internally without bulging.	(Kocurek & Kocurek, 2023)
Airtight adhesive tape for doors and windows and window with adhesive tape	Sealing strip that uses pressure differences to improve airtightness.	(Zhenyu, 2023)
Sealing closure for an opening of a coking oven	Expanding sealing strip compensating for heat-induced deformation.	(Dix, 1978)
Pressurized heat exchange ventilation	Polymer-film sealing combined with controlled overpressure ventilation.	(Aiyama & Ueki, 2006)

3.3 Technical Analysis

To gather the necessary knowledge about how the technical parts of the system function, a technical analysis was conducted. This section establishes the required overpressure and quantifies the expected leak rate, followed by an assessment of how this leakage affects the enclosure's sealing requirements.

3.3.1 Overpressure

While the overpressure applied in the current tent was known, comparisons with other overpressure applications were made to better determine the overpressure needed for the new, larger enclosure. While the current tent operates with around 50 Pa of overpressure, it also fluctuates significantly due to movements and, therefore, volume changes in the tent. Therefore, this pressure is aimed to maintain an overpressure margin so that sufficient overpressure is ensured even when robot movements causes the tent to expand and pressure falls. Cleanrooms for comparison typically utilise a differential pressure of only 7.5-15 Pa, but are also more concerned with particle concentrations of different particle sizes rather than gases coming through.

However, some clear guidance could be derived from the standard SS-EN 60079-2. This standard that concern explosive environments states that 50 Pa of differential pressure is required to ensure that an explosive environment cannot penetrate into enclosures containing sparking equipment. The standard considers all flammable atmospheres and, therefore, even gases with low molecular weight such as hydrogen. This implies that 50 Pa is sufficiently high to guarantee that even the most difficult to keep out gases cannot penetrate (Elstandard, 2015).

These findings indicate that 50 Pa is a suitable overpressure to design the enclosure for. Because not only is it high enough to guarantee to keep out even the most penetrating and dangerous gases, but it is also not unreasonably high for this particular application, since it is similar to what is currently being used by Permanova. However, taking into account safety factors and standard engineering practice, it was decided to apply a safety factor of two, so a design pressure of 100 Pa was used in simulations and during the concept development.

3.3.2 Leak Rate

One of the most central requirements attained from the interview with Permanova was regarding the leak rate of the enclosure, Section 3.1.1. They also mentioned that argon consumption is a significant cost factor, so any leakage should be minimised, see Section 3.1.1.

To put the requirement on the total maximum leak rate of 283 L/min into perspective, it can be expressed as an average leak rate per meter of seam. If only considering seams between the panels, the total length of seams is 124.4 m, which corresponds to an average leak rate of 283/124.4=3.08 L/min/m. While if seams both between and through the active panels are included, the total length increases to 511.4 m, reducing the average leak rate to just 0.75 L/min/m.

This can be compared with the flow predicted by the Hagen–Poiseuille equation for laminar viscous flow through a thin rectangular slit:

$$Q = \frac{w\,h^3}{12\,\mu\,L}\,\Delta P$$

where the volumetric flow rate Q depends on the slit width w, gap height h, flow-path length L, dynamic viscosity μ, and pressure differential ΔP. Using the dynamic viscosity of argon at room temperature ($\mu \approx 2.2 \times 10^{-5}$ Pa·s (The Engineering ToolBox, 2026)), a slit 1 m long and 60 mm deep with gap widths of 0.1, 0.3, and 0.5 mm yields corresponding volumetric flow rates of approximately 0.38, 20.2, and 47.3 L/min, respectively. This suggests that unsealed seams pose a big risk for large amounts of leakage and would require very tight tolerances on construction and fabrication.

3.4 Today's Solution

To understand what today's solution looks like, and what this project must adapt in order to operate in an inert overpressurised environment, each part of the existing system was analysed. The components considered within the scope of this project are the structural skeleton supporting the enclosure, the passive panels forming the walls and roof, and the active panels ensuring operational safety throughout the process. The outside of the enclosure is shown in Figure 3.1.

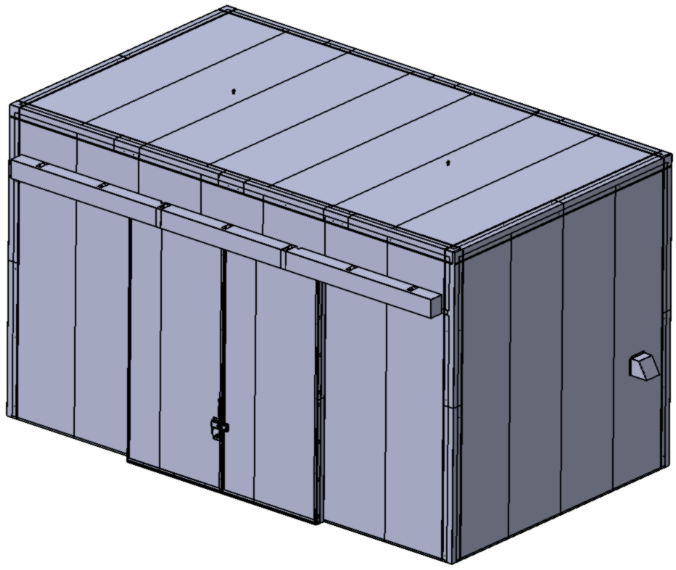


Figure 3.1: Outside today's enclosure

3.4.1 Skeleton

The skeleton of the enclosure is located between the passive and active panels and serves as the main load-bearing structure and mounting interface for all panels. The skeleton consists of 80 mm wide square steel beams with a 10 mm thick steel plate welded to each end, as can be seen in Figure 3.2. The plates are then bolted together to connect the beams into the skeletal framework. In addition, two tensioned wires are attached to the roof structure to provide supplementary support and increase overall roof stiffness and stability, as shown in Figure 3.3.

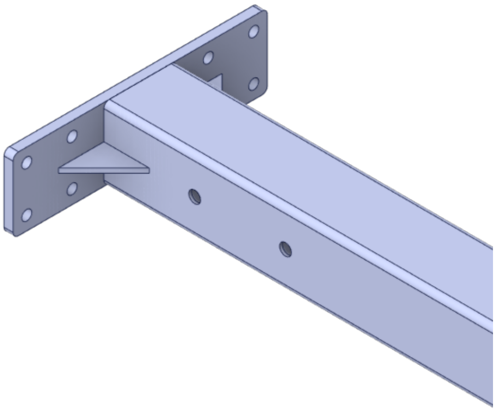


Figure 3.2: Steel beam with plate

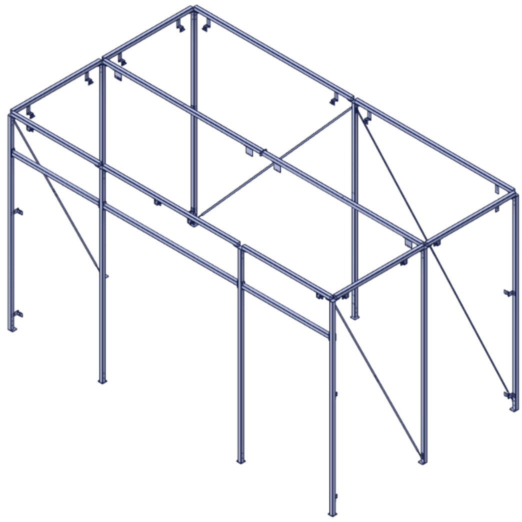
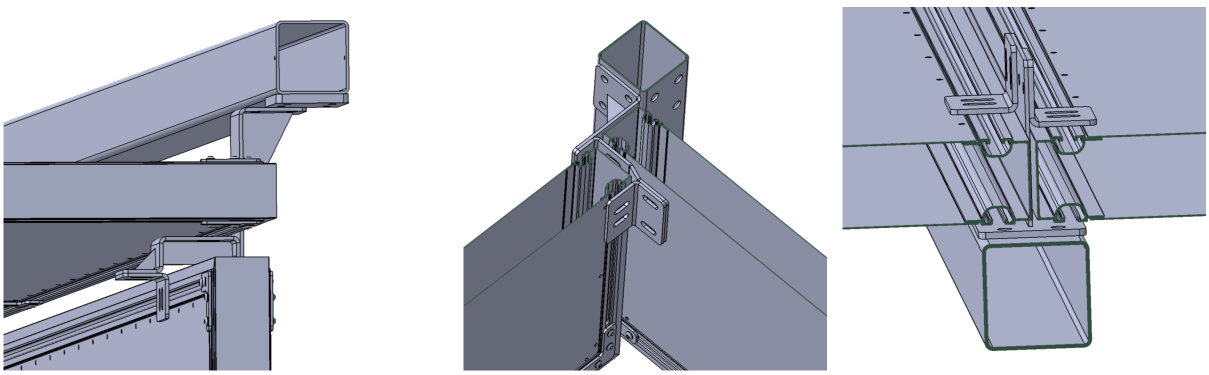


Figure 3.3: Whole skeleton

To mount the active panels to the skeleton, bracket assemblies consisting of two or three stacked brackets are used to connect the front side of the panels to the underlying structure, as can be seen in Figure 3.4. This configuration is required to ensure assembly feasibility and accessibility, as the skeleton becomes concealed by the panels once installed, preventing rear access. The mounting brackets protrude between adjacent panels, forming significant gaps, especially at the ceiling and corners where the gap is 40 mm and 22 mm respectively, and are attached to the front face of the panels using T-nuts.



(a) Ceiling **(b)** Corner **(c)** Between panels

Figure 3.4: Attachment of panels to the frame

3.4.2 Passive Panels

The passive panels are outsourced components purchased from an external supplier. This limits Permanova's ability to modify or adapt their design; instead, the enclosure must be designed around the existing panel geometry.

These panels are sandwich structures consisting of two metallic sheets with a core of insulating material in between and interlocking edge profiles. They are designed to withstand laser exposure for a specified duration, providing personnel with enough time to shut down the system before the laser burns through the panel and poses a risk to personnel or equipment outside the enclosure. The core material does not ignite when exposed to the laser; instead, it carbonises, reducing the fire hazard.

3.4.3 Active Panels

With only passive panels, an operator must continuously monitor the process to shut it down if the laser behaves unexpectedly. However, larger build volumes also result in significantly longer build times, making continuous manual supervision impractical. To address this, Permanova has developed active panels that perform this monitoring automatically.

The active panels incorporate a laser sensor purchased from an external supplier. The sensor requires a completely dark and empty cavity to function correctly. Based on these requirements, Permanova designed a panel consisting of an aluminium frame and steel sheet components, into which the sensor is mounted.

Although multiple variants exist with slightly different dimensions, a typical panel measures approximately 2 × 4 m and is divided into four sections, as shown in Figure 3.5. The aluminium frame consists of custom T-slotted aluminium extrusions with recessed steps for the steel sheets and is assembled using T-slot bracket elements. The central extrusions, referred to as struts, contain holes to allow light transmission between sections, as shown in Figure 3.6. To verify sufficient light coverage, Permanova performed puncture tests using the laser at 20 worst-case locations, confirming that the sensor responds correctly across the entire panel.

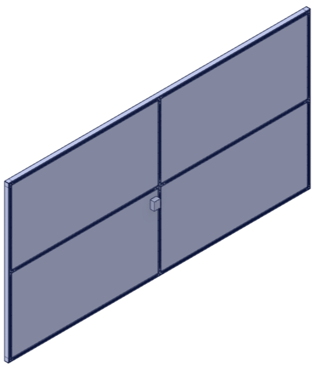


Figure 3.5: Active panel

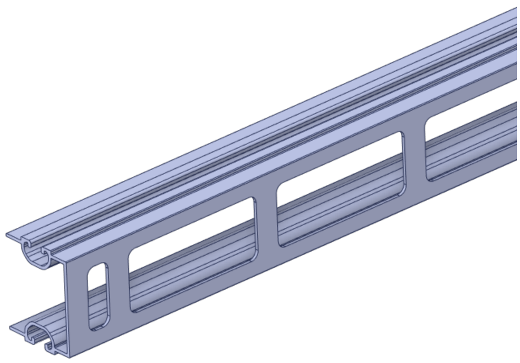


Figure 3.6: T-slots and holes in struts

3.4.4 Tent

In today's system, the inert environment is contained using a separate small pressurised tent-like enclosure. The top of the tent is attached to the robot tool, and its base is attached to the build plate. This allows the deposition tooling to move around freely while ensuring the build volume is always fully enclosed in a fully inert atmosphere.

Because the tent is attached to the moving robot, its shape and therefore volume are always changing. These movements cause pressure spikes and drops throughout the printing process. The pressure quickly returns, however, since any pressure drop will be restored by the inflow of additional argon, while any pressure increase will increase the leak rate, forcing out excess argon.

4

Requirements and System Evaluation

In this chapter, the system is defined, along with the requirements and desires placed on the solution. It also includes an analysis of today's solution and the areas that need development.

4.1 Functional Analysis

The functional tree, seen in Figure 4.1, illustrates each sub-function required to enable printing larger build volumes, including those at before, during, and after operation. Because the overall system is extensive and many functions are not directly tied to the project's aim, the scope is restricted to the green-marked stages in the tree, with emphasis on maintaining an inert environment during operation. Although not every sub-function directly contributes to the main aim, they still need to be accounted for in the design process. Overlooking them could result in an enclosure that fails to meet critical requirements; for example, the solution must ensure sufficient laser safety and must not interfere with the robot during AM. Furthermore, to simplify the problem and meet the strict project timeline, specific functions related to the enclosure's door and cable feedthroughs have been excluded from the scope, despite their role in maintaining the environment inert.

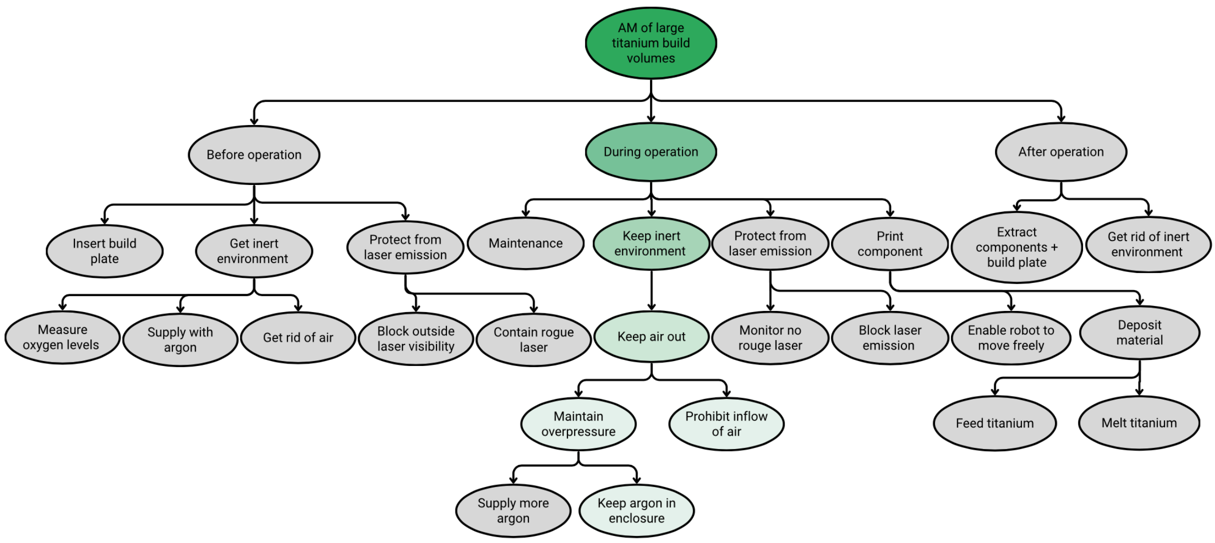


Figure 4.1: Functional Tree

4.2 Requirement Specification

After the functional tree had been developed, a requirements specification was created according to the method described in Section 2.2.2. It presents all requirements and desires for the enclosure and is shown in Table 4.1, where R/D indicates whether a criterion is a requirement (R) or a desire (D). The specification also includes requirements not directly related to achieving an inert environment but, nevertheless, necessary due to other enclosure functions and design boundary conditions. These ensure that proposed concepts are compatible with the overall system and feasible for use in Permanova's production. The requirements are based on the preliminary study in Section 3.

Table 4.1: Requirement specification. PPM refers to parts per million, and pcs refers to pieces.

No.	Criterion	Description	R/D	Rank	Value	Unit	Verification Method	Source
1	Fire Hazard	No visible combustible materials in laser area	R		0	pcs	Visual verification	Permanova
2	Overpressure	Min. overpressure at 283 LPM inflow	R		100	Pa	Physical test	Permanova
3	O_2 Level	Max O_2 Level in enclosure	R		200	PPM	Physical test	Permanova
4	Humidity	Must operate in low humidity	R		5	%	Review of Supplier Documentation	Permanova
5	Temperature	Operating temperature	R		20-55	°C	Review of Supplier Documentation	Permanova
6	Suppliers	Suppliers based in EU/USA	D	5	100	%	BOM review	Permanova
7	Chemical Safety	Comply with relevant AFS chemical-handling regulations	R		100	%	Review of supplier documentation	AFS
8	Cost	Ensure cost efficiency	D	1	-	-	Cost assessment	Project group
9	Laser Safety Class	Required emission classification	R		Class 1		IEC 60825	Permanova
10	Lifespan	Of Sealing Material	D	2	5	years	Review of supplier documentation	Defined by project group
11	Lifespan	Of Enclosure	D	4	20	years	Fatigue analysis & review of maintenance	Permanova
12	Environmental Impact	Follow Guidelines	R				14000 ISO	GKN
13	Size	Enclosure dimensions (length×width×height)	R		8×5×5	m	CAD	Permanova
14	Robot Accommodation	% restricted volume	R		0	%	CAD	Permanova
15	Assembly	Max assembly personnel required	R		2	ppl	KIM-MHO	Permanova
16	Assembly Time	Max assembly time for enclosure	D	3	80	h	Time studies	Permanova
17	Design	Dual light barriers with unobstructed cavity.	R		2	pcs	CAD	Light Sensor
18	Obstructed Light	Sensor visibility for pre-burn shutdown	R		15	ms	Test on 20 worst spots & sensor reachability analysis	IEC 60825-4 (4.3.2 a)
19	Cavity Distance	Clearance within panel	R		35	mm	CAD	Light Sensor

4.3 Evaluation of Today's Solution

To evaluate the ability and needs for improvement for today's solution to maintain an overpressurised inert environment, assessments of leakage paths, structural response and seal serviceability were conducted.

4.3.1 Sealing Assessment

Because the enclosure's ability to meet the required overpressure, leak-rate, and oxygen-level specifications relies heavily on it being sufficiently airtight, an initial visual inspection of potential leakage paths was conducted using a CAD model provided by Permanova to determine where the largest sources of leakage were located. The most critical potential leakage paths were identified at the floor, ceiling, corners, and panel interfaces, as illustrated in Figure 4.2. In the figure, the different areas are colour-coded to distinguish the leakage regions: green indicates the ceiling, orange represents the interfaces between panels, yellow highlights the corner regions, and red marks the floor connection. These gaps ranged from 5 mm to 45 mm, which orders of magnitudes larger than the gap sizes indicated as acceptable in Section 3.3.2, where even 0.5 mm gaps were shown to far exceed the allowable leakage limit. 3.3.2

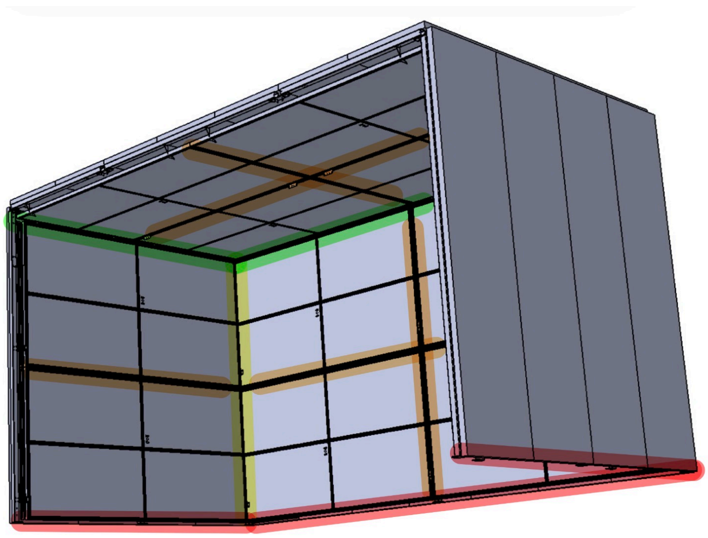


Figure 4.2: Identified potential leakage paths in the current panel solution.

An additional assessment examined whether the active panels could be considered airtight. Although their light-sealed design initially assumed airtightness, the analysis showed that the EPDM sealing strip contains microscopic gaps and paths that prevent complete airtightness. While these gaps are too small for light to pass through, they still allow minor air leakage over time. The panels can therefore not be regarded as fully airtight in subsequent analyses. This also suggests that the air trapped inside the panels may leak into the enclosure, complicating the maintenance of an inert environment. The analysis indicates that the active panels require improved sealing, and all identified leakage paths must be effectively sealed to ensure the integrity of the overpressurised environment.

4.3.2 Structural Assessment

To address uncertainties regarding the structure's ability to withstand the loads caused by the overpressure requirement and how the deformation of the panels would affect the cavity distance requirement, static structural simulations were performed. These simulations were conducted on individual components to identify potential failure points.

Subsequent static structural simulations of the active panels, with the four corners of the model constrained in translation but free in rotation, showed that when subjected to a 100 Pa overpressure load, the steel sheets deform up to 6.4 mm, which is less than the 10 mm height of both the T-slot feature and edge of the strut holes, which is the limit for when the deformation would negatively impact the minimum cavity distance. The aluminium frame deforms 3.1 mm, which would offset the strut hole, but because these holes are 40 mm tall, there is a 5 mm margin to the minimum cavity distance requirement that the deformation does not exceed. Although these deformations would not compromise the cavity distance requirement, they are nonetheless quite significant even at this low overpressure and their margins are slim, highlighting the panels as a potential area for further refinement.

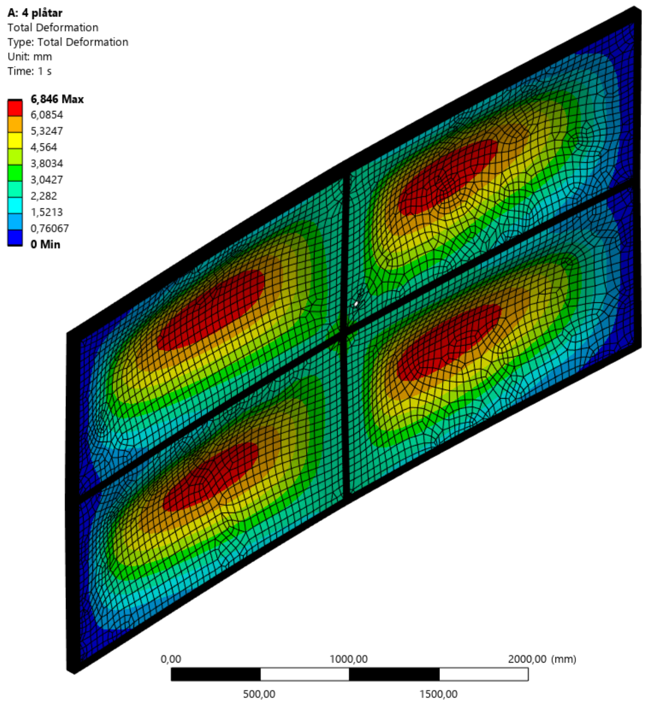


Figure 4.3: Deformation simulation of today's active panel

To evaluate the structural capability of the skeleton, a simulation of a quarter of the enclosure's skeleton was used to capture how the forces from the required overpressure, as well as the weight of the active panels, affects the skeleton. Only the back left quarter of the skeleton was modelled, using symmetry boundary conditions along the two mid-planes, as the geometry and loading is mostly symmetric. This was done to investigate whether or not the skeleton could withstand the required overpressure as well as if the deformation was excessive enough to potentially cause additional challenges for the development of a sealing solution.

The simulation suggests very little deformation on most of the skeleton, with only one area with major deformation on the upper right corner, as can be seen in figure 4.4. Because of the symmetry, the entire skeleton experiences only two major deformations, one centred around the top middle of each of the two long side walls, where the structure deforms outward by about 22 mm. This large deformation would not only cause large gaps and leakage, but also likely not be possible without breaking, tearing or permanently deform the brackets connecting the wall and ceiling panels, or parts of the panels themselves.

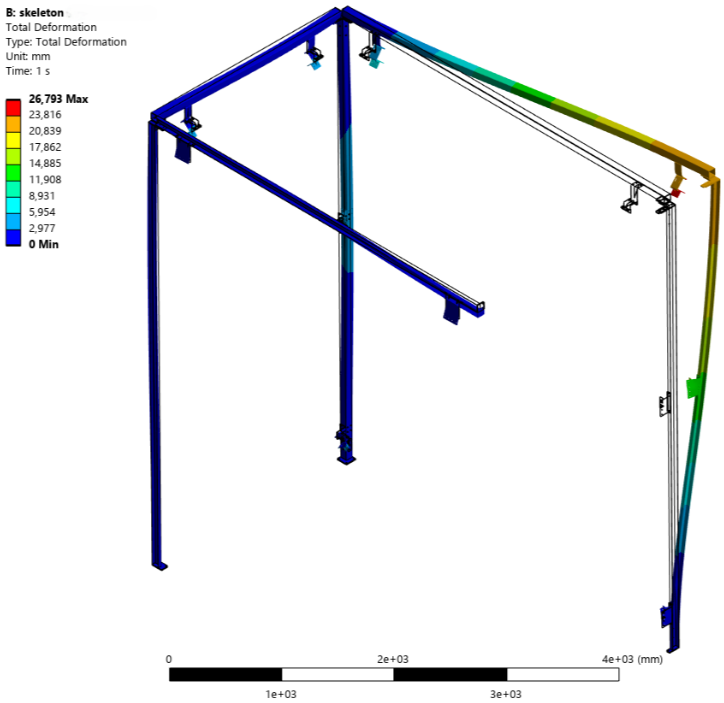


Figure 4.4: Deformation simulation of today's skeleton

These structural evaluations therefore indicate that today's solution requires some improvements to the active panels and skeleton for it to be able to structurally withstand the additional load from the overpressurised environment.

5

Concept Development

This chapter presents the development of solutions to the previously identified problems. It covers concepts for the placement of the sealed barrier, how the enclosure should handle additional loads, and methods for sealing gaps.

5.1 Sealing Solution

To determine the preferred design and placement of the sealing barrier, a brainstorming workshop was conducted, using the method described in Section 2.4.1. Four main alternatives emerged: sealing the passive panels, sealing the active panels, enlarging the existing tent, or implementing a structured tent enclosing all machines, inspired by the patent 'Pressurized heat exchange ventilation' in Section 3.2.3.

Since the enclosure must maintain an extremely low oxygen level, the seal must be placed as close as possible to the inert environment to avoid trapping air that could compromise it. Sealing the passive panels was therefore considered counterproductive, since the air-filled active panels are located on their inner side.

Furthermore, enlarging the current tent was rejected due to handling difficulties and incompatibility with the double-sided build plate, described in Section 3.4.4.

The remaining concepts, sealing the active panels or using a structured tent, were evaluated against the requirements in Section 4.2. Sealing the active panels met all requirements, whereas the structured tent failed on two points: the fire risk associated with covering machines in flammable material, and the risk of flexible tent walls interfering with robot motion due to pressure variations.

In conclusion, sealing the active panels was the only technically robust concept that accommodates the robot's motion and fully complies with all requirements.

5.2 Structural Reinforcement

Since the sealing barrier will be applied to the active panels, the primary structural issues fall into two categories. First, the panels must be improved so they do not deform beyond what the seals can tolerate or to a degree that impairs sensor performance. Second, the skeleton must be strengthened to adequately support the panels and prevent them from shifting too much relative to each other. Excessive shifting would otherwise compromise the seal.

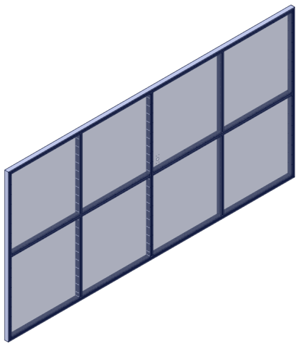
5.2.1 Active Panels

Three solutions were generated through brainstorming (described in Section 2.4.1) to improve the structural reinforcement of the active panels. The first was to increase the thickness of the panel plates. The second was to add more struts to reduce the span of the plates while also reinforcing the frame. The third solution was to seal the entire panel. To find which solution is most suitable, they were first looked into in more depth, then compared based on their performance in static simulations.

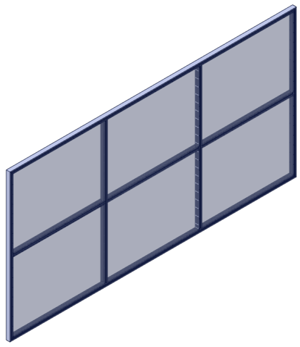
5.2.1.1 Deeper Investigation of Solutions

Thicker plates:
Using thicker plates would result in an increase in the weight of the plates; switching from 1.5 mm to 2 mm would amount to 25 % heavier plates. Today the plates weigh about 25-28 kg per plate which adds up to 200-224 kg for the whole panel. Increasing the panel's weight by 25 % would therefore impose a significant additional load on the structure, especially on the roof.

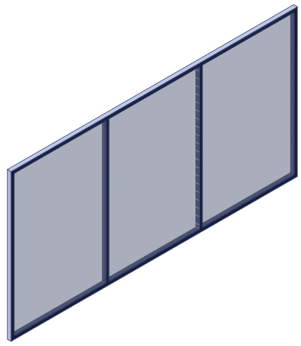
Increasing number of struts:
For the solution involving additional struts, four concepts were generated using the brainstorming method described in Section 2.4.1. The concepts shown in Figure 5.1 consist of panels with three, six, or eight plates rather than the four used in today's design, as described in Section 3.4.3. For easier identification, the concepts were named 8 Plates, 6 Plates, 3 Short, and 3 Tall based on their geometry. None of these concepts would significantly increase weight or cost, but they would require minor redesigns.



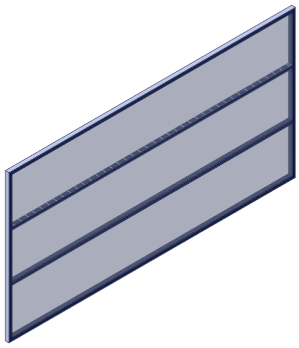
(a) 8 Plates



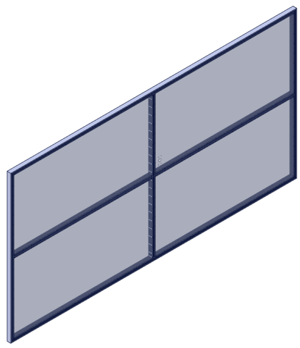
(b) 6 Plates



(c) 3 Short



(d) 3 Tall

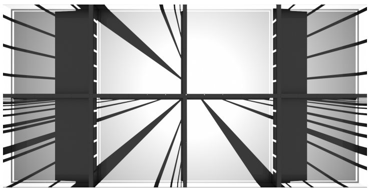


(e) Today’s Design

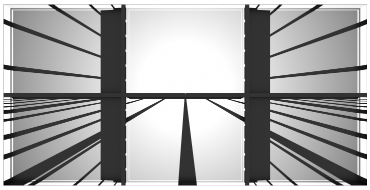
Figure 5.1: Active Panel Designs

However, adding more struts increases the risk of obstructed light within the panels. This can directly reduce the light sensors’ capability to detect a rogue laser. To accurately assess the extent of this problem, light simulations were performed using the 3D modeling and rendering software Blender. In these simulations, a lamp was placed inside the panels’ CAD models at the exact sensor position to determine which areas the light could reach. The new panel designs were then compared with today’s solution. Any new design that performs on par with or better than the existing one is treated as potentially viable, although additional physical tests on the 20 poorest-performing locations will be required for confirmation. In contrast, any design that underperforms relative to today’s solution is excluded from further consideration.

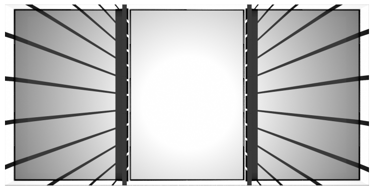
The simulation outcomes are shown graphically in Figure 5.2. The quantitative results in Table 5.1 indicate the percentage of light that is obstructed, defined as the fraction of dark pixels at different light intensity thresholds. The results indicate that all proposed designs exhibit a lower percentage of blocked light compared to today’s solution at thresholds below 15 %. Although some concepts show higher percentages at higher lightness thresholds, the lower thresholds are considered more relevant, as they better represent the actual dark spots.



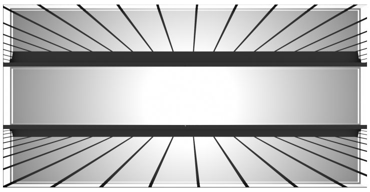
(a) 8 Plates



(b) 6 Plates



(c) 3 Short



(d) 3 Tall

(e) Today's Design

Figure 5.2: Obstructed Light Simulation

Table 5.1: Light Simulation

Lightness (%)	3 Short	3 Tall	6 Plates	8 Plates	Today's design
5	0	0	0.01	0	0.51
10	0.44	0.31	0.82	0.3	1.95
15	1.45	0.96	2.67	2.53	3.33
20	8.53	11.09	15.58	6.59	6.8
25	20.11	19.52	28.99	36.8	20.44
30	20.23	19.74	29.21	37.09	20.82
35	20.31	19.93	29.38	37.26	21.07
40	20.39	20.08	29.51	37.39	21.29
45	20.47	20.24	29.68	37.53	21.56

Seal entire panel:
Sealing both sides of the panels would mean that the air inside the panel from the assembly will be trapped inside. This air would be compressed when the front plates deform from the pressure load, which would in turn increase the pressure inside the panel and not only exert a pressure load on the back plate, but also push back on the front plate. This approach would distribute the deformation across both the inner and outer plates, rather than concentrating the load solely on the inner plate and thereby better withstand the pressure load from the overpressure.

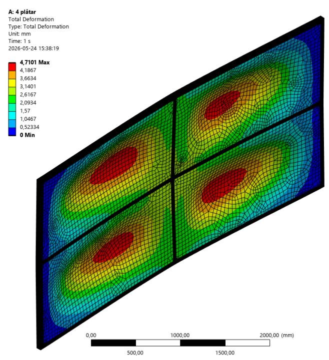
5.2.1.2 Static Simulations

Structural simulations of the different active panels provided values for the four critical measurements; frame deformation (frame def), frame separation (frame sep), inner plate deformation (inner plate) and outer plate deformation (outer plate), where frame separation measures how much the gap between two panels increase, while the other three measures out of plane deformation for the three different parts. The resulting values are presented in Table 5.2 along with respective values for today's design (ref in the table). The first column shows plate thickness, the second shows the number of plates, and the third indicates whether it is airtight or not. The first entry is the simulation results for today's design and serves as the reference for the percentage columns, while the second entry is an airtight version of it. The third and fourth entries are variants with 2 or 3 mm thick plates instead of the original 1.5 mm, while the last four are the concepts: 8 plates, 6 plates, 3 Short and 3 Tall mentioned above in Section 5.2.1.1.

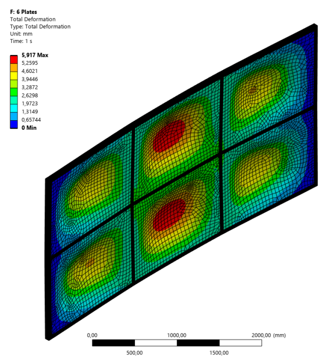
Table 5.2: Simulation measurements of active panel concepts

Thick	N.o	Airtight	Frame def.		Frame sep.		Inner Plate		Outer Plate	
(mm)	plates	yes/no	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
1.5	4	no	3.12	ref	0.055	ref	6.43	ref	3.10*	ref
1.5	4	yes	3.06	-2	0.049	-11	4.69	-27	3.84	24
2.0	4	no	2.70	-14	0.043	-23	4.31	-33	2.68*	-14
3.0	4	no	2.38	-24	0.034	-39	2.46	-62	2.36*	-24
1.5	6	no	2.81	-10	0.047	-14	5.92	-8	2.81*	-9
1.5	8	no	3.12	0	0.065	17	4.77	-26	3.09*	0
1.5	3S	no	2.28	-27	0,078	41	8.29	29	2.28*	-26
1.5	3T	no	1.36	-56	0.021	-62	2.10	-67	1.35*	-56

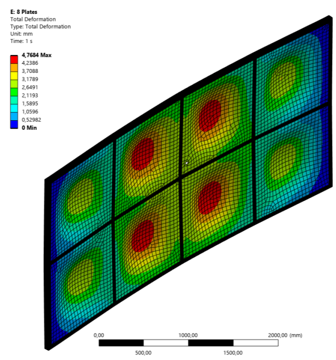
*at the frame contact point (plate follows frame def. without bulging)



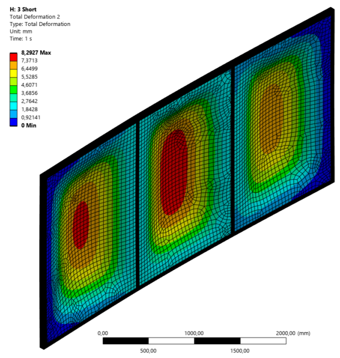
(a) Airtight



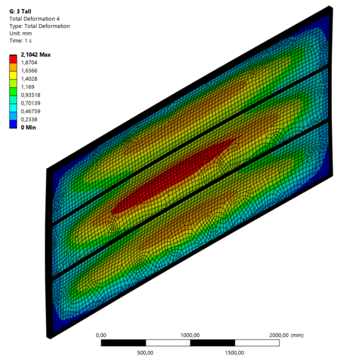
(b) 6 Plates



(c) 8 Plates



(d) 3 Short



(e) 3 Tall

Figure 5.3: Deformation simulations of active panels

The results show that the frame deformation is very small compared to the length and width of the panel, however not insignificant compared to the thickness and margins of the light holes in the frame. It also shows that the contribution to frame separation from the bending of the panel frame is very small. The most significant deformation is the bending of the plates. The largest reduction in deformation of the inner plate was achieved when using 3 tall plates and when the plate was thickened to 3 mm, being reduced by approximately 4.3 and 4 mm respectively. Airtight, 2 mm thick plate and 8 plates all provided a decent reduction around 1.6-2.1 mm. The worst reduction was observed with 6 plates, which reduced it by only 0.5 mm, while 3 short plates actually experienced greater plate deformation than today's panel. The outer plate only bends significantly when the panel is airtight due to this being the only scenario when the outer plate experiences a pressure load, in the other cases, its deformation is caused by the deformation of the frame. However, even when airtight and experiencing pressure load, the effects are much smaller than for the inner plate. It only deforms 3.8 mm, which is 0.7 mm less than when not airtight.

Furthermore, the simulation indicated minimal stress levels across the panels, with today's panel showing stress concentrations of around 75 MPa under the 100 Pa pressure load and the airtight panel showing 77 MPa. These significant stresses occurred only at some edges of rigidly joined contact surfaces between struts. These stress locations and magnitudes from the simplified model are not representative of the real assembly which would connect the struts using screws and T-nuts, but provide a sufficient conservative estimate. For context, the current roof panels show stress concentrations up to 102 MPa under gravity loading alone.

Moreover, even with these high stress estimates, light fatigue simulations indicated lifespans of at least 10 000–100 000 load cycles before any risk of fatigue. This corresponds to 1.3-13 cycles per day over the required 20-year lifetime, which is well above even the most conservative estimate of one cycle per day. Taken together, these findings indicate that neither stress nor fatigue is expected to pose a risk during the operational lifespan of the panels.

The simulations show that although 3 Tall plates and 3 mm thick plates have a much greater relative improvement compared to today's solution, they all perform relatively similarly since the difference between the largest and smallest deformation improvement is just 2.5 mm. Meanwhile, to achieve this additional improvement the panels either require a rework of their frame design for the 3 tall solution, or the weight would almost double by using 3 mm plates.

The airtight solution, by contrast, retains the original frame design and does not increase the weight. The only modification is the addition of an airtight seal on the panel's second side, which is a minor change and straightforward to implement, since one side already requires such a seal.

It is important to note the configuration of the static simulations and their associated limitations, as these directly influence the obtained results. First, the simulations simplified the system by separating the simulations of the active panels from those of the supporting skeleton. This separation was necessary due to simulating the complete system being too demanding for the computers. Consequently, the simulations do not capture the complete interactive behaviour of the system, such as how deformation of the skeleton and brackets effects the deformation of the panels, and vice versa.

In the finite element model, the plates of the panels are represented using two-dimensional plane elements, whereas all other components are discretised with three-dimensional solid elements. Due to their slender, elongated, and geometrically complex shape, the struts in particular required a very large number of finite elements, which substantially increased the overall computational effort.

The investigation of mesh refinement did not reveal a clear convergence of the results. As a consequence, the final element sizes were selected based on the smallest mesh that the simulations feasibly could manage. These mesh sizes were nevertheless considered acceptable for the intended comparative purpose of the simulations, since the observed variation of the results with respect to mesh refinement, although approximately linear, exhibited a relatively small gradient.

5.2.2 Skeleton

Since the only significant deformation was on the top centre of the front and back walls, and since they deform in opposite directions, a simple solution is to add a beam connecting these points to cancel out their movement. As can be seen in Figure 5.4, this beam would have to cut across the existing roof beam. This can be solved quite simply, since the existing roof beam is already divided into two and connected with a bolted joint, so they can just be slightly shortened to accommodate the width of the new beam and bolted on and through it. Figure 5.5 shows the deformation simulation of the skeleton with an additional roof beam connecting the front and back walls. This simulation showed that the deformation decreased from 22 mm to 0.5 mm. The weight of the additional beam is approximately 34 kg, which, for comparison, is far less than for an active panel.

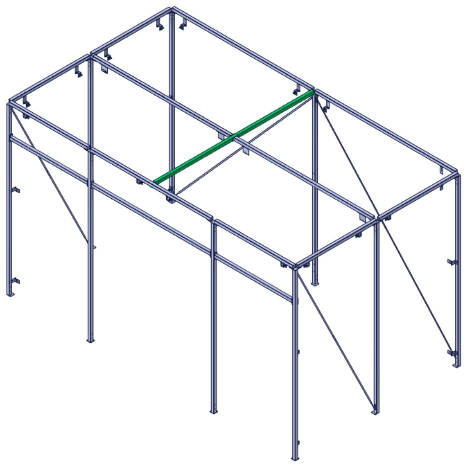


Figure 5.4: Additional roof beam

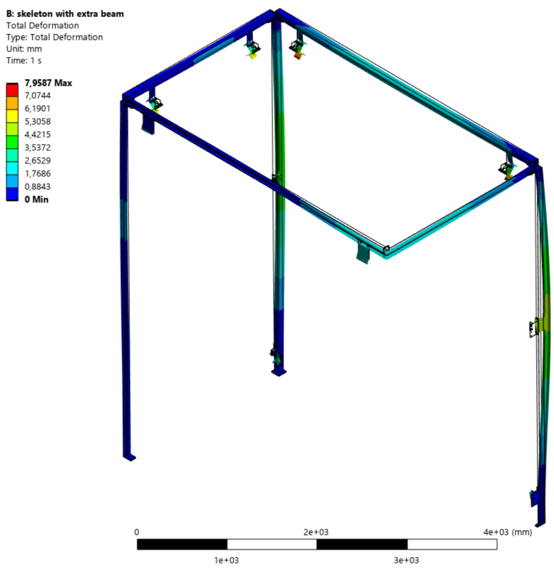


Figure 5.5: Deformation simulation of skeleton

5.3 Sealing Gaps

The visually identified gaps, defined in Section 4.3.1, were then divided into four categories based on their geometric characteristics and the specific problems they present. The first category, ”Corners”, includes the intersections between perpendicular panels. The remaining categories are ”Floor Connectors”, ”3-Way Corner”, and ”Between Panels”. The categories can be seen colour-coded in Figure 5.6, with ”Corners” in dark green, ”Floor Connectors” in bright green, ”3-Way corner” in yellow, and ”Between Panels” in orange.

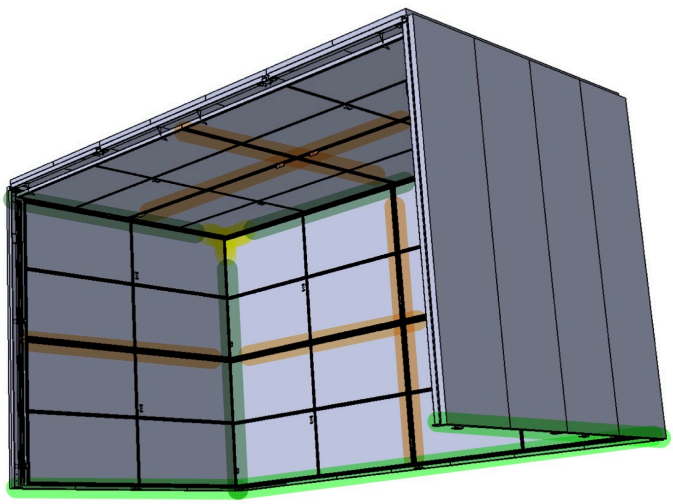


Figure 5.6: Gaps Categories

5.3.1 Concept Generation

Solutions for the first three categories were generated by first defining the sub-functions for each problem area, followed by brainstorming sub-solutions for each function, as described in Section 2.4.1. These sub-solutions were then combined using morphological matrices to form complete concepts.

For the ”Between Panels” category, brainstorming (Section 2.4.1) was conducted at the system level, considering the problem as a whole. This resulted in solutions that already constituted complete concepts. This approach was chosen because the category had a limited number of sub-functions, which in turn restricted the range of possible concept variations.

5.3.1.1 Corners

The sub-functions to be addressed were how the panels should be positioned, how the gaps should be covered, and which sealing material to use. Panel positioning was defined as a sub-function due to the current lack of direct contact between panels in the corners, as described in 3.4.1. The solutions for covering the gaps consisted of different types of aluminium profiles, as shown in the sketches in Appendix A, or of leaving the gaps unsealed. The sealing materials considered were those investigated in Section 3.2.2.

The morphological matrix with the generated sub-solutions is presented in Table 5.3. By applying constraints to remove incompatible combinations, such as “X-profile” combined with “Pillar with Groove”, a total of 61 concepts were generated.

Table 5.3: Morphologic Matrix Corners

Sub-function	Sub-solutions					
Placement	Pillar		Pillar with Groove		End-to-Face	
Cover	L-Profile	T-Profile	F-Profile	X-Profile	Pillar	None
Sealing Material	Adhesive Tape	Sealants		Sealing Strip		Welding

5.3.1.2 Floor Connection

For the floor connection, the defined sub-functions were how the panels should be attached to the floor, how the gaps should be covered, and what sealing material should be used. The solutions for attaching the panels consisted either of using profiles similar to those used for gap coverage or adhesively bonding the panels directly to the floor. The different profile geometries are shown in sketches in Appendix A. The sealing materials considered were the same as those used for the corner connections, except for welding, which is not applicable to non-metallic floor materials. After eliminating incompatible combinations, 20 concepts, seen in Appendix

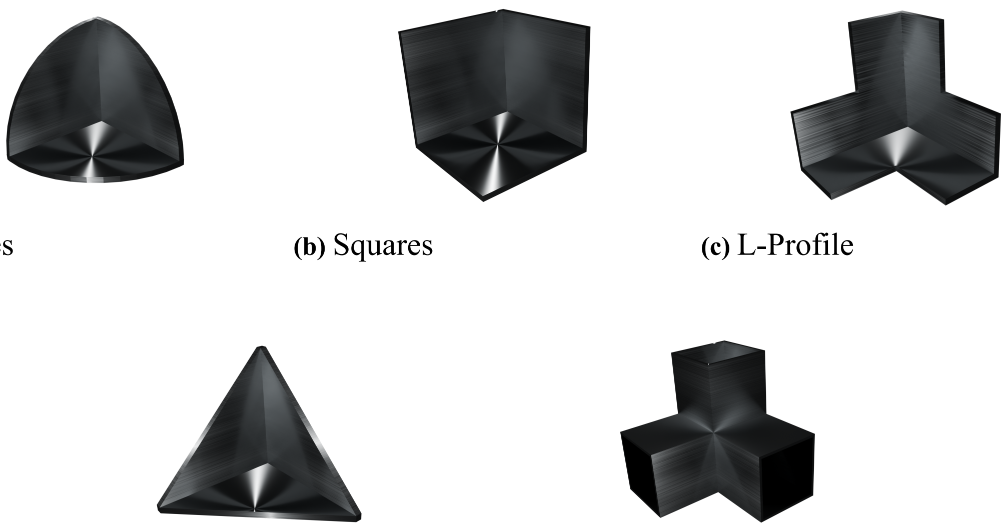
B.2, were generated using the morphological matrix shown in Table 5.4.

Table 5.4: Morphologic Matrix Floor

Sub-function	Sub-solutions				
Attachment	L-Profile	T-Profile	U-Profile	U-Profile with Flanges	Glue Stuck
Cover	L-Profile		T-Profile	Pillar	None
Sealing Material	Adhesive Tape		Sealants		Sealing Strip

5.3.1.3 3-Way Corner

At the corner where the roof or floor meets the perpendicular panel, a special three-way corner is formed. The most critical function in these corners was to cover the existing gaps. To address this, five profile concepts were generated through brainstorming. These profiles, shown in Figure 5.7, consist of different geometries.



(a) Circles **(b)** Squares **(c)** L-Profile

(d) Triangles **(e)** Pillar

Figure 5.7: 3-Way Profiles

Additional sub-functions for this problem area include whether the component should be positioned with an overlap or edge-to-edge relative to the adjacent covers, as well as the selection of sealing material. After eliminating all incompatible combinations, 27 concepts, seen in Appendix B.2, were generated using the morphological matrix shown in Table 5.5.

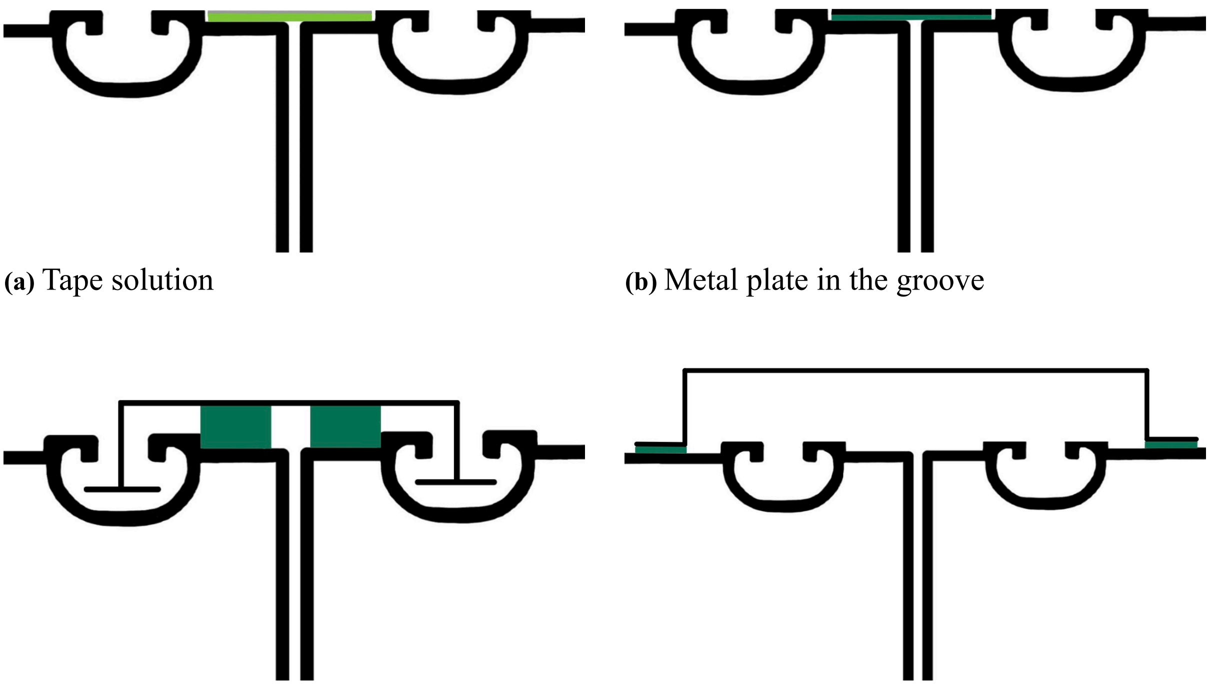
Table 5.5: Morphologic Matrix 3-Way Corner

Sub-function	Sub-solutions				
Placement	Overlap		Edge-to-Edge		
Cover	Circles	Squares	L-Profile	Triangles	Pillar
Sealing Material	Adhesive Tape	Sealants		Sealing Strip	Welding

5.3.1.4 Between Panels

When developing solutions to address gaps and leakage risks between adjacent panels, four concepts were generated. The concepts were developed through a brainstorming session, described in Section 2.4.1, in which the project group discussed the functional requirements that the solutions needed to fulfil. The solutions were required to seal gaps of varying sizes while spanning across two adjacent panels.

The proposed solutions include using metallic tape and various designs based on a metal profile combined with a sealing material. The profile-based solutions consist of a metal plate positioned in the groove, a metal plate fixed in T-slots, and a metal cover placed over the T-slots to encapsulate the interface. The concepts are shown in Figure 5.8.



(a) Tape solution

(b) Metal plate in the groove

(c) Metal plate in T-slots

(d) Metal plate over T-slots

Figure 5.8: Between Panels concepts

5.3.2 Concept Screening

To see which concepts are the most suitable and have the best potential, the remaining concepts from the different morphological matrices were put into additional matrices. The different categories concepts was named with the first letter of the category follow with a number based on how many concept there was in that category, all concepts and descriptions on them can be seen in Appendix B.2.

5.3.2.1 Fulfilling Criteria

The first evaluation step was to determine whether the concepts fulfilled the criteria derived from the requirement specification presented in Section 4.2. The criteria are listed below:

1. Fire Safety
2. Pressure Leak Rate
3. Humidity
4. Temperature
5. Chemical Safety
6. Laser Safety Class
7. Environmental Impact
8. Assembly
9. Obstructed Light

To check if the concepts fulfilled the criteria, elimination matrices were used. Four matrices were created, one for each category. The only categories containing concepts that did not fulfil all criteria were the “Corners” and ”3-Way Corner” categories. However, ”Environmental Impact” and ”Chemical Safety” are criteria that should be considered for all categories in later stages when selecting products and materials across all categories, to ensure that the final solution fulfils these requirements.

Corners:
The eliminated concepts were excluded either because they contained visible sealing material, which would increase the risk of fire, or because they obstructed light, as in the cases where a pillar or a grooved pillar was used. These concepts introduced a risk of not providing active protection around the entire laser area, which is not permitted according to the requirement specification. Another type of concept that was eliminated involved the use of tape directly in the corner without a cover, as this posed a significant leakage risk due to the difficulty of achieving a consistently airtight application in such an area. Lastly, all solutions using welding were eliminated due to it being classified as ”Hot work” as mentioned in Section 3.2.2.4 and

therefore needing more than two people for assembly. After evaluating the matrix, 10 concepts remained.

3-Way Corner:
In the morphological matrix for the 3-Way corner, all solutions using welding as a sealing material were eliminated. This is due to it needing more than two people for assembly due to it being classified as ”Hot work” as mentioned in Section 3.2.2.4. This results in 19 concepts remaining.

5.3.2.2 Most Suitable Concept

To evaluate how the concepts perform relative to one another, Pugh matrices were used alongside discussions. The criteria in the Pugh matrices that concepts were compared on were:

- Assemblability
- Lifespan of Sealing Material
- Ability to Re-do Sealing Material
- Sealing Capability
- Risk of Trapped Air
- Simplicity of design

Corners:
The concepts remaining after the corner elimination matrix were evaluated using three separate Pugh matrices, see Appendix B.3.1, each with a different reference concept. These references were selected to provide a variety of perspectives and to ensure the evaluation was as objective as possible. The chosen references were:

1. **C12** - End-to-Face with L-profile and Sealants
2. **C5**- End-to-Face with F-profile and Sealing Strip
3. **C9** - End-to-Face with T-profile and Sealants

These matrices combined indicated that the two most suitable solutions for sealing the corners were “End-to-Face” with an L-profile combined with either “Sealants” or “Sealing Strip”. However, when these two concepts were directly compared in a Pugh matrix, “Sealants” showed a slightly better overall performance. Based on this direct comparison, “Sealants” was selected as the final solution for corner sealing.

Floor Connections:
Since all floor concepts met the requirements, they were all evaluated using Pugh matrices to identify the most suitable alternative based on the previously defined criteria. Three matrices were created using different reference concepts. The matrices can be seen in Appendix B.3.2. The order of the matrices, together with their corresponding reference concepts, was:

1. **F3** - U-profile with flanges with no cover and Adhesive Tape
2. **F8**- T-profile with L - Profile and Sealants
3. **F14** - L-profile with L - Profile and Sealing Strip

Two concepts were eliminated after the first two matrices due to significantly poorer performance compared to the remaining alternatives. After the final matrix, the remaining concepts were F2, F3, F5, F8, F9, F15, and F16, all of which were variants of similar design solutions.

To further narrow the concepts, additional discussions and investigations were conducted. This led to the elimination of all concepts that used U-profiles, or U-profiles with flanges, because the sealing material could not be replaced or reapplied without dismantling entire wall sections. Since the sealing material is expected to have a shorter lifespan than the enclosure, this solution would reduce the enclosure's overall service life. Tape solutions were also eliminated after further consideration, as tape is sensitive to external damage and poses a risk of edge lifting from nearby movement of machines or personnel.

This resulted in two remaining concepts, F8 and F15, where the only difference was whether the attachment should use an L-profile or a T-profile. The difference between these alternatives was considered minimal, as the additional flange of the T-profile was not expected to improve the sealing performance. Since L-profiles were also selected for the corner solutions, the decision was made to use L-profiles throughout the enclosure to maintain consistency across the design.

3-Way Corners:
The use of L-profiles at both the corners and the floor connections means that the ”3-Way Corner” solution must also be compatible with L-profiles. As a result, the use of pillars was directly eliminated, leaving 16 concepts remaining. Since both the corner and floor connection solutions also use sealants as the sealing material, it was considered beneficial for the ”3-Way Corner” concepts to use the same material unless another material with more favourable properties was identified, which was not the case. This further narrowed the concepts down to these 6 concepts:

- **W2**- Triangles Overlap with Sealants
- **W5** - L - profile Edge-to-Edge with Sealants
- **W8** - L - profile Overlap with Sealants
- **W11** - Squares Edge-to-Edge with Sealants
- **W14** - Squares Overlap with Sealants
- **W16** - Circles Overlap with Sealants

When comparing these solutions, it became clear that overlap designs were preferable to edge-to-edge designs. Overlap configurations create a maze-like leakage path for air, reducing leakage risk and seam-related issues. The remaining question was therefore whether to use L-profiles, squares, circles, or triangles.

The circular and triangular concepts were considered mainly as aesthetic alternatives, and were also more difficult and expensive to manufacture. These concepts were therefore eliminated. Since the L-profile concept can essentially be viewed as a square profile with a smaller square section removed, the square profile was considered both cheaper and easier to manufacture. Consequently, concept W14 was selected to move forward with.

Between Panels:
When evaluating the most suitable solution for sealing between the panels, the concepts were further analysed for functionality and feasibility. This analysis showed that a metal plate placed in the T-slots would not be feasible, since these slots are used to mount the panels, so the plate would interfere with the fastening system.

The concept involving a metal plate covering the entire interface could potentially work; however, it was considered more advantageous to place the metal plate within the gap itself. This approach uses the gap both to position the plate and to keep it in place throughout its lifespan.

When comparing the use of tape versus a metal plate with a sealing material, the metal plate solution was found to offer superior structural advantages and easier assembly. In addition, the ”Sealant” had already been identified as the most suitable sealing material in other parts of the system. Maintaining a limited number of material types and assembly methods is also beneficial in terms of assembly and purchase. Consequently, the concept of a metal plate with a sealant placed within the gap was selected for further development.

5.3.3 Choice of Sealant

Since all sealing interfaces rely on a sealant, it is essential to select a product that meets the functional requirements and performs consistently across the enclosure. Based on interviews (see Section 3.1), three sealant types were evaluated: polyurethane, silicone, and an SMX hybrid polymer.

Table 5.6 summarises representative products for each type: Sikaflex from Sika (Sika, n.d.-a) for the polyurethane, Fix ALL Flexi from Soudal (Soudal, n.d.) as the SMX hybrid polymer, and Sikasil-C from Sika (Sika, n.d.-b) as the silicone one. The compared properties include elongation at break, hardness, and other relevant characteristics.

The sealant must combine flexibility with sufficient rigidity to secure the profiles while allowing movement, making high elongation and high hardness desirable. Although Fix ALL Flexi performs best in these metrics, Sikaflex offers comparable performance while being safer to handle, as Fix ALL Flexi needs good ventilation and is classified as hazardous in its data sheet (Soudal, n.d.). In addition, Sikaflex is already used by Permanova and is well established in their processes. Sikaflex was therefore selected for the project.

Table 5.6: Sealant Comparison

Material	Curing time (3 mm deep)	Elongation at break	Vibration capability	Movement capability	Hardness (Shore A)	Safety procedure	Application
Sikaflex (Sika, n.d.-a)	<24 h	500 %	Good	-	40	Wash hands on contact	Interior sealing & bonding applications, ideal for metals.
Fix ALL Flexi (Soudal, n.d.)	≤ 24 h	750 %	Excellent	± 20 %	45 ± 5	Needs good ventilation	Elastic bond for vibrating structures; adheres to most surfaces
Sikasil (Sika, n.d.-b)	24 h	600 %	Good	± 25 %	~20	-	Construction & sanitary joints. Not resistant to stress or abrasion

5.4 Final Solution

When all partial solutions had been developed, they were compiled into a complete final solution and evaluated to determine whether the specified requirements could be met. The sealing design for the floor and corners is shown in Figure 5.9, while the sealing solution between the panels is presented in Figure 5.10. Together, these figures illustrate the overall implementation of the sealing concept.

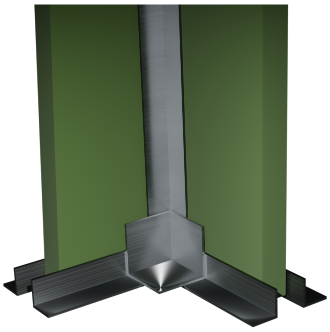


Figure 5.9: The solution in a corner

Figure 5.10: Solution between panels

5.4.1 BOM

The final solution requires almost no modifications to the enclosure's existing BOM and primarily consists of additional components. The only modification is replacing the EPDM sealing strip with an airtight sealant. Apart from this, no components are redesigned or replaced; the solution only introduces supplementary parts. The BOM for these additions is as follows:

- L-profiles, used to cover gaps in perpendicular corners (Figure 5.11)
- Metal plates, used to cover gaps between adjacent surfaces (Figure 5.12)
- Square 3-Way Corner pieces, used to cover gaps in the 3-Way Corners (Figure 5.13)
- Roof beam, to provide additional support (marked in green in Figure 5.14)
- Sikaflex, used to seal all gaps and make the enclosure airtight

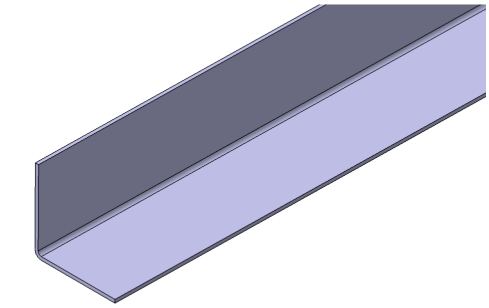


Figure 5.11: L-profile

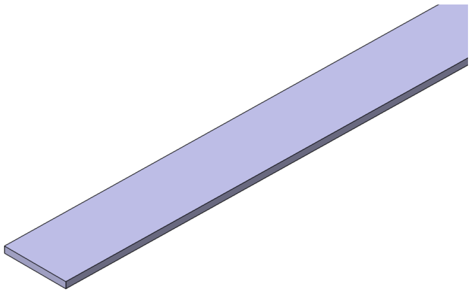


Figure 5.12: Metal plates

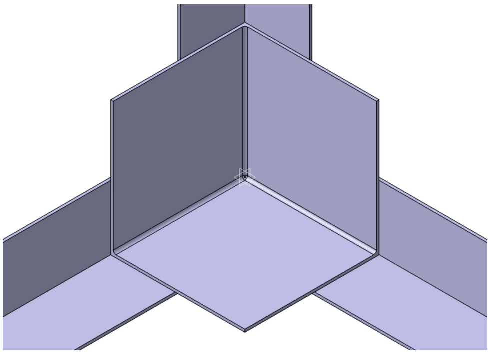


Figure 5.13: Square 3-way corner

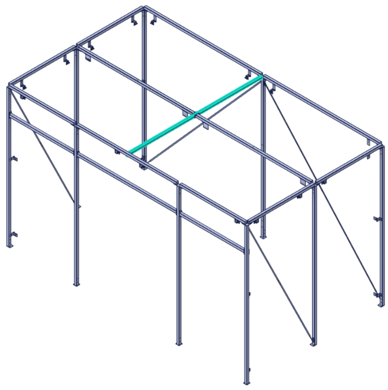


Figure 5.14: Additional roof beam

5.4.2 Verification of Solution

To assess whether the complete final solution could be realized and function as intended, it was compared against the requirement specification presented in Section 4.2. The solution was evaluated using the defined verification methods to determine if the target values were fulfilled. In several cases, particularly those involving a physical prototype, experimental testing, or production-oriented analyses such as assembly assessment, time studies, and environmental impact, verification could not be completed within the project's time frame. These requirements are therefore labelled as *Not Verified*, and further verification is advised prior to implementation. Where it was possible to apply alternative verification methods, these were employed to the fullest extent feasible within the project, and the associated requirements are marked as *Partially Verified*. An overview of all verification outcomes is provided in Table 5.7.

Table 5.7: Verification of Criterion

No.	Criterion	Verification Method	Verification Status	Verification Comment
1	Fire Hazard	Visual Verification	Verified	No visible combustible material in laser area
2	Overpressure	Physical Test	Not Verified	Physical tests could not be performed within the project scope
3	O_2	Physical Test	Not Verified	Physical tests could not be performed within the project scope
4	Humidity	Review of Supplier Documentation	Verified	All materials are compatible with low humidity environments
5	Temperature	Review of Supplier Documentation	Verified	Solution compatible with required temperatures
6	Suppliers	BOM review	Verified	EU/US supplier availability for all materials
7	Chemical Safety	Review of Supplier Documentation	Verified	All materials are AFS-compliant
8	Cost	Cost assessment	Not Verified	Outside the project scope
9	Laser Safety Class	IEC 60825	Verified	No panel re-design & no major deformation
10	Lifespan (Sealing Material)	Review of Supplier Documentation	Verified	5+ year lifespan with correct application
11	Lifespan (Enclosure)	Fatigue analysis & review of maintenance	Partially Verified	Further analysis on maintenance is required
12	Environmental Impact	Follow Guidelines	Not Verified	A life cycle assessment was outside the projects scope
13	Size	CAD	Verified	Enclosure dimensions unaffected
14	Robot Accommodation	CAD	Verified	No obstruction to robot movement
15	Assembly	KIM-MHO	Not Verified	Physical tests could not be performed within the project scope
16	Assembly Time	Time Studies	Not Verified	Physical tests could not be performed within the project scope
17	Design	CAD	Verfied	No re-design of panels
18	Obstructed Light	Test on 20 worst spots & sensor reachability analysis	Partially Verified	No panel redesign; further testing needed due to deformation
19	Cavity Distance	CAD	Partially Verified	No panel redesign; further testing needed due to deformation

6

Discussion

This chapter discusses the extent to which the defined objectives were fulfilled, as well as challenges and problem areas identified during the project. The discussion also addresses the underlying reasons for these challenges and reflects on how alternative approaches might have influenced the outcome.

6.1 Fulfilment of Objectives

The objectives of this project were the following:

- Identify what poses a risk of air leakage into the enclosure.
- Evaluate the structural load from overpressurisation.
- Identify and evaluate potential solutions for sealing and reinforcing the enclosure.
- Evaluate effects on passive and active protection panels from overpressurisation.
- Identify and evaluate potential solutions for leakage-free active protections panels.

All objectives have been addressed during the course of the project, ranging from identifying the primary leakage risks to developing and evaluating solutions aimed at minimizing these risks. The only objective not fully explored concerns the effects of overpressurisation on the passive panels. This is a direct consequence of the design decision to let the active panels function as the primary sealing barrier. As a result, the active panels absorb the full load from the overpressure, meaning that the passive panels are not significantly affected and therefore fall outside the critical scope of the analysis.

The final objective-evaluating potential solutions for leakage-free active protection panels-was addressed, although only to a limited extent. The chosen approach was to adapt the existing panel design using a more suitable sealing material, as this solution met the requirements while remaining compatible with the current enclosure. Although alternative active panel concepts could have been explored to fully eliminate the risk of trapped air, such an investigation would have required a broader scope and additional time. Given the project's constraints and its focus on adapting the existing system rather than developing a new one, the chosen level of detail was considered appropriate.

6.2 Narrowing Down the Scope

At the start of the project, the scope was defined too broadly, aiming to develop an entirely new enclosure rather than adapting the one currently used by Permanova. This resulted in time being spent on areas that did not contribute to the core aim. For instance, investigations were conducted into whether the passive panels were required to meet safety regulations, and it was concluded they were not. Another area explored was whether the current laser sensor was the most suitable option. The time and resources spent on these tasks could instead have been utilized to learn and perform more complex simulations, or to focus on other essential parts of the enclosure, such as the door, which are required for a complete and applicable solution.

6.3 Simulations

When conducting the simulations, it became clear at an early stage that we did not initially possess the knowledge required to perform some of the more advanced simulations, such as how to model a panel containing air. As a result, additional research was necessary before the work could proceed. This learning curve was time-consuming, both due to the research itself and the trial-and-error phase required to understand and successfully implement the simulations.

Additionally, without prior experience with advanced modelling, we were unaware of established methodology and best-practice for setting up such models. This likely impacted the quality of the simulations and the accuracy of the results. It also led to the very high computational demands, which in turn forced the simulations to be limited to isolated sections rather than large comprehensive models of the entire system.

Another aspect of the simulation work that required significantly more time than anticipated was the technical issues encountered in the software. Both Blender and Ansys caused recurring error messages, unexpected shutdowns, and difficulties when launching the programs. As a result, extensive communication with the university IT support was required in order to resolve the problems. This process was time-consuming, both due to waiting for technical assistance and the efforts spent troubleshooting the issues independently.

Since these simulations were critical to the project and necessary for evaluating today's solution and the new concepts, conducting them was not an error in judgment. However, the initial project planning failed to account for the substantial time investment required, highlighting a need for early adjustments to the scope and schedule. Furthermore, potential software instabilities and our limited initial expertise should have been included in a risk management analysis. This would have enabled a proactive response to technical issues as they arose, or alternatively, the establishment of a backup plan in the event of total software failure.

6.4 Gathering of Information

Throughout the project, balancing independent concept generation with the utilisation of Permanova's internal expertise proved challenging. In an effort to avoid bias and prevent being overly influenced by the company's existing solutions, consultation with Permanova was intentionally limited. In retrospect, this strict separation was a misjudgment. While it fostered independent thinking, it also led to knowledge gaps that could have been avoided with better preparation and more frequent follow-up questions. Consequently, the decision-making process and the search for answers became unnecessarily time-consuming. A key takeaway is that future projects would benefit from a more integrated approach, where industry expertise is utilised more effectively to drive efficiency without compromising objective evaluation.

6.5 Requirements Verification

Although multiple requirements could not be tested and verified the confidence in most aspects of the the proposed solution is quite high due to large margins to the requirement limits even with a safety factor of two.

For instance, although the actual total leak rate has not been directly tested, it is expected to be very low and comfortably within the allowable limit, since the enclosure should in theory be essentially airtight. Consequently, there should be a substantial safety margin, even if minor flaws or imperfections introduce some small leakage points. Despite this assessment, because the seals are so critical for the leak rate, and therefore functionality and performance of the enclosure, the leak rate should be quantified in closer detail. Either through simulations or physical tests.

Similarly, although the deformation of the sealant or the formation of gaps between panels could not be simulated or calculated, they are considered to be constrained by the deformation of the skeleton. Since the deformation of the reinforced skeleton itself is confidently estimated to be very small, the resulting relative movement and gap formation between panels is also expected to be more than small enough for the sealant and cover plates to handle.

How well the airtight panels meet the requirement regarding cavity distance remains quite uncertain however, and requires further study before compliance can be confirmed. This is not only due to uncertainties in the simulations arising from various simplifications, lack of mesh convergence, and similar issues, but also because of uncertainty regarding how well the airtight panels will maintain their internal pressure over prolonged periods.

7
Conclusion

This chapter presents a summary of the thesis and the development project, followed by recommendations for future work to make the proposed solution more comprehensive and readily implementable.

7.1 Summary of Work

The project concludes that to adapt today's laser enclosure into an inert enclosure suitable for AM, an overpressure of 50 Pa is required to prevent contaminants or air from penetrating the enclosure. The most critical leakage paths were identified around the floor, ceiling, corners, and panel interfaces. To mitigate this, a comprehensive sealing solution utilising a set of metal profiles (L-profiles and plates) and polyurethane sealant was proposed.

Furthermore, the structural response of the skeleton and the active panels to the overpressure load was assessed by simulations, leading to two primary design recommendations:

1. The implementation of an additional roof beam to reinforce the structural skeleton, effectively reducing the maximum wall deformation from 22 mm to 0.5 mm.
2. Sealing the active panels to make them completely airtight, thereby compressing the internal air volume during deformation to create a counteractive, pressure-balancing load.

Combined, these results demonstrate that establishing and maintaining an overpressurised inert environment within the existing laser enclosure has high potential to be feasible, offering excellent compatibility with the current system geometry without requiring a complete structural redesign.

7.2 Future Work

Future work should address areas that could not be fully explored due to the time limitations of this project. Several aspects remain unverified or fall outside the scope of this thesis and therefore represent natural next steps for continued development.

Physical verification of the proposed solution is essential. This includes tests to determine whether the light can reach all areas of the panel, even when it deforms. Additionally, experiments are needed to assess the realism and reliability of the simulation results. Such validation should involve both more advanced simulations with proper convergence studies and full-scale physical testing of the enclosure. Physical tests would also provide insights into the perceived safety of the enclosure for nearby personnel-for example, whether it produces unexpected sounds or deforms in ways that could cause concern.

Furthermore, additional work is needed to develop components not included in this thesis. This includes the design of doors capable of withstanding the overpressure without excessive deformation, as well as sealing solutions that still allow for repeated opening and closing. Additional components, such as feedthroughs, should also be investigated to ensure full system functionality. Another area of interest is to examine how maintenance is performed and whether it could be carried out without shutting down and restarting the operation. This could improve operational efficiency and reduce argon consumption.

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A

Appendix A

A.1 L-Profile Sketch

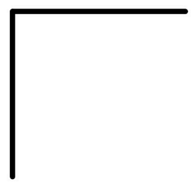

Figure A.1: L-Profile Sketch

A.2 T-Profile Sketch

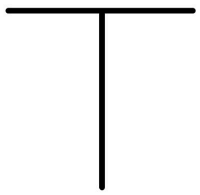

Figure A.2: T-Profile Sketch

A.3 F-Profile Sketch

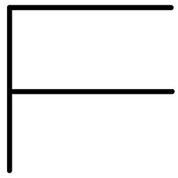

Figure A.3: F-Profile Sketch

A.4 Pillar Sketch

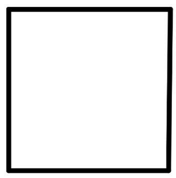

Figure A.4: Pillar Sketch

A.5 Pillar-with-grooves Sketch

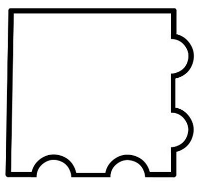

Figure A.5: Pillar With Groove Sketch

A.6 X-Profile Sketch

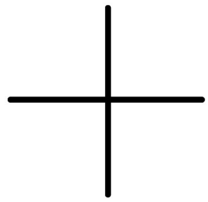

Figure A.6: X-Profile Sketch

B

Appendix B

B.1 Elimination Matrices

B.1.1 Floor Connections

Table B.1: Elimination Matrix Floor Connections

Solution	Criterion									Keep/
	1	2	3	4	5	6	7	8	9	Discard
F1	+	+	+	+	+	+	+	+	+	Keep
F2	+	+	+	+	+	+	+	+	+	Keep
F3	+	+	+	+	+	+	+	+	+	Keep
F4	+	+	+	+	+	+	+	+	+	Keep
F5	+	+	+	+	+	+	+	+	+	Keep
F6	+	+	+	+	+	+	+	+	+	Keep
F7	+	+	+	+	+	+	+	+	+	Keep
F8	+	+	+	+	+	+	+	+	+	Keep
F9	+	+	+	+	+	+	+	+	+	Keep
F10	+	+	+	+	+	+	+	+	+	Keep
F11	+	+	+	+	+	+	+	-		Discard
F12	+	+	+	+	+	+	+	-		Discard
F13	+	+	+	+	+	+	+	-		Discard
F14	+	+	+	+	+	+	+	+	+	Keep
F15	+	+	+	+	+	+	+	+	+	Keep
F16	+	+	+	+	+	+	+	+	+	Keep

B.1.2 Corners

Table B.2: Elimination Matrix Corner

Solution	Criterion									Keep/
	1	2	3	4	5	6	7	8	9	Discard
C1	-									Discard
C2	-									Discard
C3	-									Discard
C4	+	+	+	+	+	+	+	+	+	Keep
C5	+	+	+	+	+	+	+	+	+	Keep
C6	+	+	+	+	+	+	+	+	+	Keep
C7	+	+	+	+	+	+	+	+	+	Keep
C8	+	+	+	+	+	+	+	+	+	Keep
C9	+	+	+	+	+	+	+	+	+	Keep
C10	+	+	+	+	+	+	+	+	+	Keep
C11	+	+	+	+	+	+	+	+	+	Keep
C12	+	+	+	+	+	+	+	+	+	Keep
C13	+	+	+	+	+	+	+	+	+	Keep
C14	-									Discard
C15	-									Discard
C16	-									Discard
C17	+	+	+	+	+	+	+	+	-	Discard
C18	+	+	+	+	+	+	+	+	-	Discard
C19	+	+	+	+	+	+	+	+	-	Discard
C20	+	+	+	+	+	+	+	+	-	Discard
C21	-									Discard
C22	-									Discard
C23	-									Discard
C24	+	+	+	+	+	+	+	+	-	Discard
C25	+	+	+	+	+	+	+	+	-	Discard
C26	+	+	+	+	+	+	+	+	-	Discard
C27	+	+	+	+	+	+	+	+	-	Discard
C28	+	+	+	+	+	+	+	+	-	Discard
C29	+	+	+	+	+	+	+	+	-	Discard
C30	+	+	+	+	+	+	+	+	-	Discard
C31	+	+	+	+	+	+	+	+	-	Discard
C32	+	+	+	+	+	+	+	+	-	Discard
C33	+	+	+	+	+	+	+	+	-	Discard
C34	+	+	+	+	+	+	+	+	-	Discard
C35	+	+	+	+	+	+	+	+	-	Discard
C36	+	+	+	+	+	+	+	+	-	Discard

B.2 Solutions from Morpheus

B.2.1 Corners

Corners							
#	Placement	Cover	Sealing Materials	#	Placement	Cover	Sealing Materials
C1	End-to-Face	None	Welding	C31	Pillar With Groove	L - Profile	Welding
C2	End-to-Face	None	Sealing Strip	C32	Pillar With Groove	L - Profile	Sealing Strip
C3	End-to-Face	None	Sealant	C33	Pillar With Groove	L - Profile	Sealant
C4	End-to-Face	None	Adhesive Tape	C34	Pillar With Groove	L - Profile	Adhesive Tape
C5	End-to-Face	Pillar	Welding	C35	Pillar	None	Welding
C6	End-to-Face	Pillar	Sealing Strip	C36	Pillar	None	Sealing Strip
C7	End-to-Face	Pillar	Sealant	C37	Pillar	None	Sealant
C8	End-to-Face	Z - Profile	Welding	C38	Pillar	None	Adhesive Tape
C9	End-to-Face	Z - Profile	Sealing Strip	C39	Pillar	Pillar	Welding
C10	End-to-Face	Z - Profile	Sealant	C40	Pillar	Pillar	Sealing Strip
C11	End-to-Face	Z - Profile	Adhesive Tape	C41	Pillar	Pillar	Sealant
C12	End-to-Face	F - Profile	Welding	C42	Pillar	X - Profile	Welding
C13	End-to-Face	F - Profile	Sealing Strip	C43	Pillar	X - Profile	Sealing Strip
C14	End-to-Face	F - Profile	Sealant	C44	Pillar	X - Profile	Sealant
C15	End-to-Face	F - Profile	Adhesive Tape	C45	Pillar	X - Profile	Adhesive Tape
C16	End-to-Face	T - Profile	Welding	C46	Pillar	Z - Profile	Welding
C17	End-to-Face	T - Profile	Sealing Strip	C47	Pillar	Z - Profile	Sealing Strip
C18	End-to-Face	T - Profile	Sealant	C48	Pillar	Z - Profile	Sealant
C19	End-to-Face	T - Profile	Adhesive Tape	C49	Pillar	Z - Profile	Adhesive Tape
C20	End-to-Face	L - Profile	Welding	C50	Pillar	F - Profile	Welding
C21	End-to-Face	L - Profile	Sealing Strip	C51	Pillar	F - Profile	Sealing Strip
C22	End-to-Face	L - Profile	Sealant	C52	Pillar	F - Profile	Sealant
C23	End-to-Face	L - Profile	Adhesive Tape	C53	Pillar	F - Profile	Adhesive Tape
C24	Pillar With Groove	None	Welding	C54	Pillar	T - Profile	Welding

C25	Pillar With Groove	None	Sealing Strip	C55	Pillar	T - Profile	Sealing Strip
C26	Pillar With Groove	None	Sealant	C56	Pillar	T - Profile	Sealant
C27	Pillar With Groove	None	Adhesive Tape	C57	Pillar	T - Profile	Adhesive Tape
C28	Pillar With Groove	Pillar	Welding	C58	Pillar	L - Profile	Welding
C29	Pillar With Groove	Pillar	Sealing Strip	C59	Pillar	L - Profile	Sealing Strip
C30	Pillar With Groove	Pillar	Sealant	C60	Pillar	L - Profile	Sealant
				C61	Pillar	L - Profile	Adhesive Tape

B.2.2 3-Way Corners & Floor Connections

3-Way Corners				Floor Connections			
#	Attachment	Placement	Sealing Material	#	Attachment	Cover	Sealing Material
W1	Pillar	Edge-to-Edge	Welding	F1	Glue Stuck	Pillar	Sealants
W2	Pillar	Edge-to-Edge	Sealing Strip	F2	Glue Stuck	L-Profile	Sealing Strip
W3	Pillar	Edge-to-Edge	Sealants	F3	Glue Stuck	L-Profile	Sealants
W4	Pillar	Edge-to-Edge	Adhesive Tape	F4	Glue Stuck	L-Profile	Adhesive Tape
W5	Triangles	Overlap	Welding	F5	U-Profile with Flanges	None	Sealing Strip
W6	Triangles	Overlap	Sealing Strip	F6	U-Profile with Flanges	None	Sealants
W7	Triangles	Overlap	Sealants	F7	U-Profile with Flanges	None	Adhesive Tape
W8	Triangles	Overlap	Adhesive Tape	F8	U-Profile	None	Sealing Strip
W9	L - profile	Edge-to-Edge	Welding	F9	U-Profile	None	Sealants
W10	L - profile	Edge-to-Edge	Sealing Strip	F10	T-Profile	Pillar	Sealants
W11	L - profile	Edge-to-Edge	Sealants	F11	T-Profile	L-Profile	Sealing Strip
W12	L - profile	Edge-to-Edge	Adhesive Tape	F12	T-Profile	L-Profile	Sealants
W13	L - profile	Overlap	Welding	F13	T-Profile	L-Profile	Adhesive Tape
W14	L - profile	Overlap	Sealing Strip	F14	L-Profile	Pillar	Sealants
W15	L - profile	Overlap	Sealants	F15	L-Profile	T-Profile	Sealing Strip
W16	L - profile	Overlap	Adhesive Tape	F16	L-Profile	T-Profile	Sealants
W17	Squares	Edge-to-Edge	Welding	F17	L-Profile	T-Profile	Adhesive Tape

W18	Squares	Edge-to-Edge	Sealing Strip	F18	L-Profile	L-Profile	Sealing Strip
W19	Squares	Edge-to-Edge	Sealants	F19	L-Profile	L-Profile	Sealants
W20	Squares	Edge-to-Edge	Adhesive Tape	F20	L-Profile	L-Profile	Adhesive Tape
W21	Squares	Overlap	Welding				
W22	Squares	Overlap	Sealing Strip				
W23	Squares	Overlap	Sealants				
W24	Squares	Overlap	Adhesive Tape				
W25	Circles	Overlap	Welding				
W26	Circles	Overlap	Sealing Strip				
W27	Circles	Overlap	Sealants				

B.3 Pugh Matrices

B.3.1 Corners

Table B.5: Corner Pugh Matrix 1

Pugh matrix 1	Concepts									
Criteria:	C4	C8	C9	C10	C11	C12	C13	C14	C15	C16
Easy assembly	-	-	-	-	-	-	-	-	REF	-
Lifespan	0	+	0	-	+	0	-	+	REF	-
Re-do sealing material	0	0	-	-	0	-	-	+	REF	+
Sealing Capeability	0	-	0	-	-	0	-	-	REF	-
Trapped Air	-	0	0	0	0	0	0	0	REF	0
Simplicity	-	-	-	-	-	-	-	-	REF	0
Σ +	0	1	0	0	1	0	0	2	REF	1
Σ -	3	3	3	5	3	3	5	3	REF	3
Σ 0	3	2	3	1	2	3	1	1	REF	2
Total	-3	-2	-3	-5	-2	-3	-5	-1	REF	-2

Table B.6: Corner Pugh Matrix 2

Pugh matrix 2	Concepts									
Criteria:	C4	C8	C9	C10	C11	C12	C13	C14	C15	C16
Easy assembly	0	REF	+	-	0	+	-	+	+	-
Lifespan	-	REF	-	-	0	-	-	0	-	-
Re-do sealing material	0	REF	-	0	0	-	0	+	0	0
Sealing Capeability	+	REF	+	0	0	+	0	0	+	0
Trapped Air	-	REF	0	0	0	0	0	0	0	0
Simplicity	0	REF	+	0	+	+	0	+	+	+
Σ +	1	REF	3	0	1	3	0	3	3	1
Σ -	2	REF	2	2	0	2	2	0	1	2
Σ 0	3	REF	1	4	5	1	4	3	2	3
Total	-1	REF	1	-2	1	1	-2	3	2	-1

Table B.7: Corner Pugh Matrix 3

Pugh matrix 3	Concepts							
Criteria:	C4	C8	C9	C11	C12	C14	C15	C16
Easy assembly	0	-	0	-	REF	+	+	-
Lifespan	0	+	0	+	REF	+	0	-
Re-do sealing material	+	+	0	+	REF	+	+	+
Sealing Capeability	0	-	0	-	REF	-	0	-
Trapped Air	-	0	0	0	REF	0	0	0
Simplicity	-	-	-	-	REF	+	+	0
Σ +	1	2	0	2	REF	4	3	1
Σ -	2	3	1	3	REF	1	0	3
Σ 0	3	1	5	1	REF	1	3	2
Total	-1	-1	-1	-1	REF	3	3	-2

B.3.2 Floor Connection

Table B.8: Floor Pugh Matrix 1

Pugh matrix 1	Concepts												
Criteria:	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F14	F15	F16
Easy assembly	-	0	REF	-	+	+	0	+	0	0	0	+	0
Lifespan	+	+	REF	+	+	+	+	+	0	+	+	+	0
Re-do sealing material	-	-	REF	-	-	0	+	0	0	0	+	-	0
Sealing Capeability	-	+	REF	-	+	+	-	+	0	+	-	+	0
Trapped Air	0	0	REF	0	0	-	0	0	0	-	0	0	0
Simplicity	-	0	REF	-	0	0	-	+	+	0	-	+	+
Σ +	1	2	REF	1	3	3	3	4	1	2	3	4	1
Σ -	4	1	REF	4	1	1	1	0	0	1	1	1	0
Σ 0	1	3	REF	1	2	2	2	2	5	3	2	1	5
Total	-3	1	REF	-3	2	2	2	4	1	1	2	3	1

Table B.9: Floor Pugh Matrix 2

Pugh matrix 2	Concepts										
Criteria:	F2	F3	F5	F6	F7	F8	F9	F10	F14	F15	F16
Easy assembly	0	0	-	-	-	REF	-	-	-	0	-
Lifespan	0	-	0	0	+	REF	-	0	+	0	-
Re-do sealing material	-	+	-	0	+	REF	+	0	+	0	+
Sealing Capeability	0	-	0	0	-	REF	-	0	-	0	-
Trapped Air	0	0	0	-	0	REF	0	-	0	0	0
Simplicity	0	0	0	-	-	REF	0	-	-	0	0
Σ +	0	1	0	0	2	REF	1	0	2	0	1
Σ -	1	2	2	3	2	REF	3	3	2	0	3
Σ 0	5	3	4	3	2	REF	2	3	2	6	2
Total	-1	-1	-2	-3	0	REF	-2	-3	0	0	-2

Table B.10: Floor Pugh Matrix 3

Pugh matrix 3	Concepts								
Criteria:	F2	F3	F5	F7	F8	F9	F14	F15	F16
Easy assembly	+	+	+	0	+	+	REF	+	+
Lifespan	-	-	-	0	-	-	REF	-	-
Re-do sealing material	-	-	-	0	-	-	REF	-	-
Sealing Capeability	+	+	+	0	+	+	REF	+	+
Trapped Air	0	0	0	0	0	0	REF	0	0
Simplicity	+	+	+	0	+	+	REF	+	+
Σ +	3	3	3	0	3	3	REF	3	3
Σ -	2	2	2	0	2	2	REF	2	2
Σ 0	1	1	1	6	1	1	REF	1	1
Total	1	1	1	0	1	1	REF	1	1

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