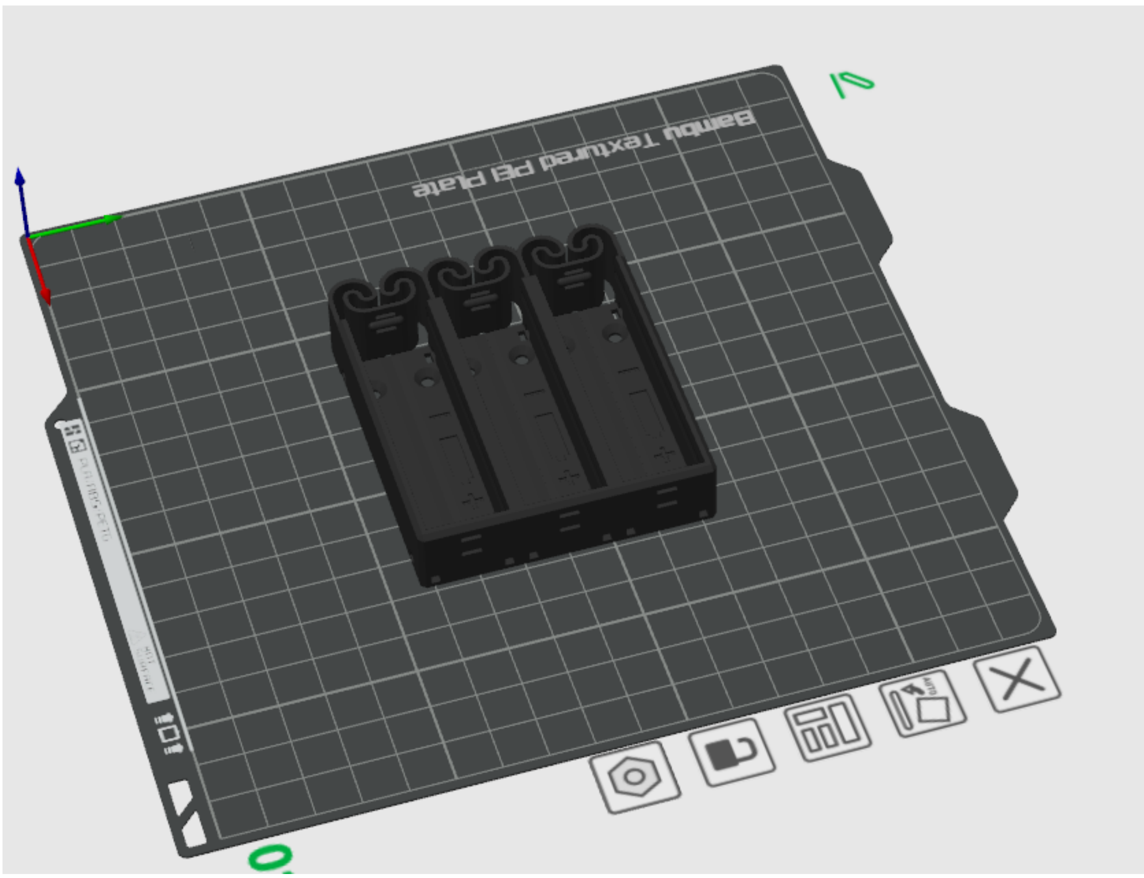
# 18650 Battery Pack Report

## 1. Introduction

This report provides a detailed description of a custom-built 3S1P 18650 lithium-ion battery pack designed for powering small electronic systems and academic projects. The pack utilizes three INR18650-26ME cells connected in series, managed by a 3S Battery Management System (BMS). All components are enclosed in a 3D-printed frame, with an XT30 connector facilitating integration into various low- to mid-power applications.




## 2. 18650 Cell Specifications (INR18650-26ME)

The selected cells are Tenpower INR18650-26ME lithium-ion batteries, known for their balance between performance, reliability, and cost. Key specifications include:

- Nominal Capacity: 2600 mAh
- Nominal Voltage: 3.7 V (range: 2.75 V to 4.2 V)
- Maximum Continuous Discharge: 15 A
- Standard Charge Current: 1.3 A (up to 2.6 A for fast charging)
- Internal Resistance: ≤25 mΩ

- Dimensions: 18.6 mm diameter, 65.1 mm length
- Weight: ~47 g per cell

These cells are based on NMC (Nickel Manganese Cobalt) chemistry, offering a good compromise between energy density, safety, and longevity, making them suitable for a range of portable energy applications.

## 3. Battery Configuration: 3S1P Arrangement

The battery pack configuration consists of three cells connected in series (3S), providing a higher overall voltage while maintaining the single-cell capacity. The key characteristics of this setup are:
- Nominal Voltage: 11.1 V (3 × 3.7 V)
- Full Charge Voltage: 12.6 V (3 × 4.2 V)
- Cutoff Voltage: 8.4 V (3 × 2.8 V)
- Total Capacity: 2600 mAh
- Total Energy: ~129.6 Wh

This configuration is commonly used in robotics, mobile electronics, and low-voltage DC systems due to its balance of voltage and portability.

## 4. Battery Management System (BMS)

To ensure safe operation, the pack includes a compact 3S 10A BMS. This unit provides essential protective features, including:
- Overcharge Protection: Activated at 4.25–4.35 V per cell
- Over-Discharge Protection: Triggered at 2.8 V per cell (verified during testing)
- Overcurrent Protection: Limits discharge current to 15 A
- Short Circuit Protection: Instantaneous disconnection upon fault
- Automatic Recovery: Self-resets after abnormal conditions are resolved

The BMS features a compact layout (53 × 14 × 4 mm) and integrates balancing wires to monitor individual cell voltages. The wiring includes:
- B− connected to the bottom of cell 1
- B1 between cells 1 and 2
- B2 between cells 2 and 3
- B+ at the top of cell 3
- P− and P+ leading to the output via an XT30 connector

This ensures safe charging and discharging and helps maintain voltage balance across cells.

## 5. Mechanical Assembly and Connectivity

Due to institutional safety policies prohibiting spot welding, a spring-loaded contact method was employed. The battery pack is housed in a custom 3D-printed enclosure that uses spring contacts and wires to create secure, removable electrical connections. This approach allows for both safety and ease of maintenance.

The XT30 connector was chosen for its compact design and ability to handle moderate current levels. Wiring was kept intentionally short to reduce resistance and thermal buildup, contributing to system efficiency and reliability.

## 6. Charging and Discharging Parameters

The charging process follows the standard CC/CV (Constant Current / Constant Voltage) protocol:
1. Constant current phase until each cell reaches 4.2 V
2. Constant voltage phase until current tapers off

Charging is typically performed at 1.3 A, with up to 2.6 A for accelerated charging. Discharging should not allow the pack to drop below 8.4 V (2.8 V per cell). The BMS will automatically disconnect the output under such conditions to protect cell health.

The 10 A current limit imposed by the BMS ensures safe operation and prevents damage from overcurrent scenarios, although it may restrict high-power loads.

| | **Rare (1)** | **Unlikely (2)** | **Moderate (3)** | **Very likely (4)** | **Guaranteed (5)** |
|---|---|---|---|---|---|
| **Catastrophic (5)** | Short circuit causes fire | Battery explosion | | | |
| **Major (4)** | Punctures of the battery | one of the wires comes loose internaly | Overheating due to overcurrent | NO FUSE | |
| **Moderate (3)** | Connector detaches during use | Cell imbalance damages one cell | | | |
| **Minor (2)** | | Incorrect voltage reading | | | |
| **Negligible (1)** | | | Loose wiring after BMS | | |

## 7. Risk assessment

The following table summarizes identified risks in the battery pack project along with the preventive measures taken to mitigate each issue:

- **Short circuit causes fire:** All wiring is insulated, and the BMS includes short circuit protection. The 3D-printed housing prevents accidental contact between conductors.

- **Battery explosion:** Proper BMS functionality ensures charge and discharge remain within safe voltage limits. Only regulated CC/CV chargers were used, and voltage thresholds were tested.
- **NO FUSE (overcurrent risk):** While no physical fuse is installed, the BMS includes overcurrent protection at 10 A. Future improvements may include adding a dedicated fuse.
- **Punctures of the battery:** The battery is securely held in a custom 3D-printed holder with no sharp edges or fasteners in contact with the cells.
- **One of the wires comes loose internally:** Wires are strain-relieved and routed to minimize movement. All joints were inspected after assembly.
- **Overheating due to overcurrent:** Wires, connectors (XT30), and the BMS are all rated for the expected current load. The BMS will disconnect if limits are exceeded.
- **Connector detaches during use:** The XT30 connector provides a firm fit and is positioned within the enclosure to reduce mechanical strain.
- **Cell imbalance damages one cell:** The BMS includes basic cell balancing features, and manual voltage checks were performed prior to assembly.
- **Incorrect voltage reading:** Measurements were verified using a multimeter, and the XT30 provides stable access to pack terminals.
- **Loose wiring after BMS:** Wiring was secured with glue and ties where necessary to avoid unintended disconnections.

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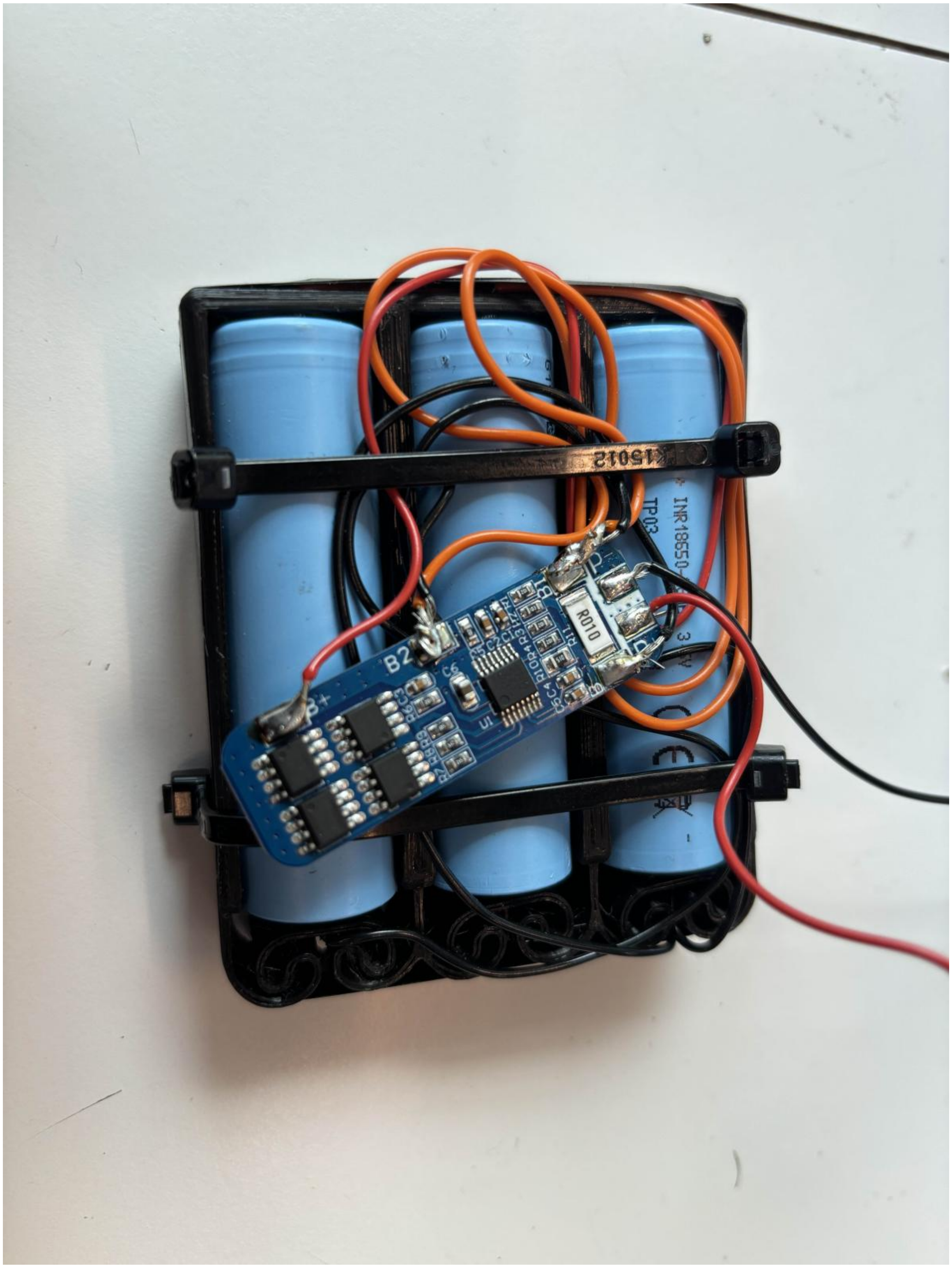
## 8. Conclusion

This 3S1P battery pack represents a practical and safe solution for mid-range portable power applications. The use of INR18650-26ME cells ensures dependable energy delivery, while the integrated BMS protects against common risks such as overcharging, deep discharge, and excessive current draw. The spring-contact design and XT30 connector offer mechanical simplicity and user safety. Overall, the pack demonstrates effective design choices suitable for academic and prototyping environments.



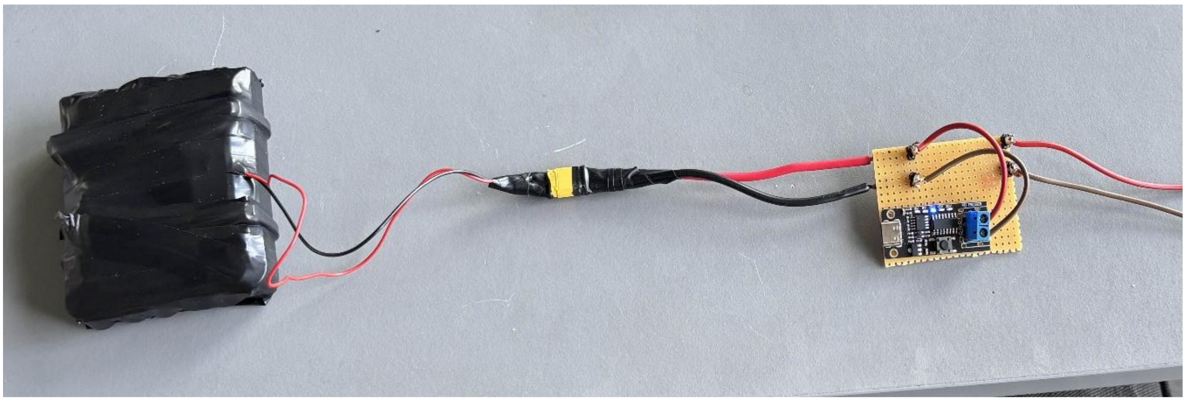

A picture of the battery ones it was soldered and all wired up.

## Appendix: Key Specifications Summary

| Parameter | Value |
|---|---|
| Configuration | 3S1P |
| Total Voltage | 11.1 V nominal, 12.6 V maximum |
| Capacity | 2600 mAh |
| Energy | ~129.6 Wh |
| Max Discharge Current | 15 A (cell limit), 15 A (BMS limit) |
| BMS Cutoff Voltage | 2.8 V per cell |
| Connector | XT30 |
| Cell Model | INR18650-26ME (Tenpower) |

## Power distribution system

As outlined in the battery section, we chose to standardize the main power supply in our system at 12 volts. While 12V is suitable for most of the power-hungry components, it is not ideal for everything—especially not for sensitive electronics like the Arduino, the encoder, and various other low-voltage subsystems. To address this, and drawing on experience from motorsport and automotive wiring harness design, a power distribution system was implemented—similar in concept to what you'd find in a racing vehicle. Just like in a car, we introduced a centralized 12V power bus to act as the backbone of the system, from which we could step down to 5V and power everything cleanly and reliably. It might be a bit overkill for a prototype, but as anyone who's tried debugging spaghetti wiring will agree, having structured power management is never a bad idea.



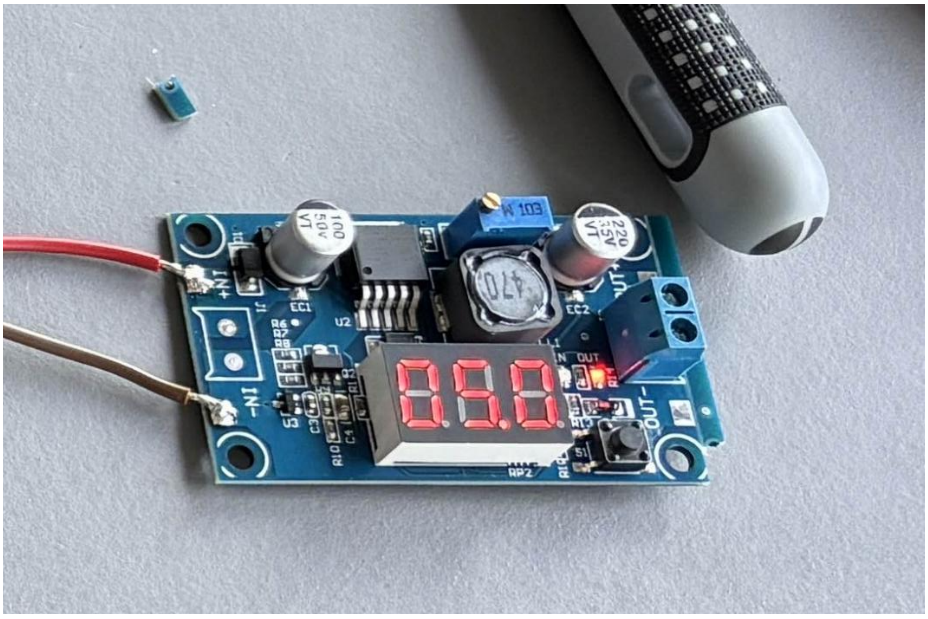
The board shown in the image is connected directly to the battery (and yes, since the photo was taken, we've added a physical fuse for safety). It essentially uses a piece of veroboard as a simple power distribution bus, where all 12V components—such as the L298N motor driver, the compressor, and the magnetic solenoid valve—are connected. Upstream from the battery, you'll also see our main 12V power source: a well-used USB-C Power Delivery (PD) board. This unit can output between 5V and 20V depending on its configuration, and we have it set up to deliver 12V at a maximum of 3A.

The PD board is primarily used to maintain the battery at around 80% charge during operation. Interestingly, this wasn't an intentional feature, but a lucky accident—as it turns out, storing lithium batteries at around 80% charge is ideal for preserving their health over time. Because the PD board is limited to 3A, the battery itself is responsible for supplying the bulk of the system's current demand. Our system is capable of drawing up to 12A at peak (see the pressure tank report and motor specifications for details).

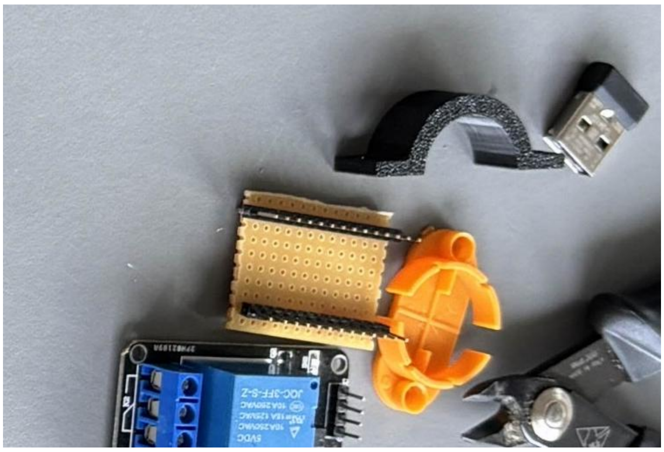
While this isn't a perfect power setup, it's a practical and safe solution for a prototype that needs to be mobile and untethered from wall power. A wired 12V mains supply might have been more stable, but would've added both complexity and risk—something we wanted to avoid for this stage of development

After the 12V power distribution board, we use a DC-DC buck converter to step the voltage down to 5V. It's one of those classic LM2596-based converters you can find pretty much everywhere online—cheap, reliable, and surprisingly robust for what it costs. The LM2596 is a step-down regulator capable of handling input voltages up to 40V and outputting a steady, adjustable lower voltage, which in our case is 5V. We use it to supply power to all the low-voltage components in the system, like the Arduino, encoder, and various sensors.

One of the reasons this converter is such a common sight in hobbyist and prototyping builds is its built-in safety features. It has both thermal shutdown and short-circuit protection, which gives some peace of mind when testing or quickly rewiring parts of the circuit. While it’s far from a high-end power module, its availability and simplicity made it the obvious choice for our project.



This provided all our 5V supply, using another power distribution board (the one you see below)



Using this board made both testing and final assembly significantly easier. Having a dedicated 5V and ground rail available simplified the wiring process, especially since it shared a common ground with the 12V supply. This allowed us to keep all components referenced to the same ground potential, which—at least in theory—should have made everything more stable and predictable.

However, issues began to appear during late-stage testing, particularly when the Arduino was no longer connected to a computer. These tests revealed that the ground connection wasn’t as solid as we initially assumed. What seemed like a clean and logical setup at the time turned out to have potential grounding issues that likely impacted stability in the standalone configuration.

This grounding issue directly affected the Y-axis control, where we used a potentiometer for position feedback. Due to the inconsistent ground reference, the readings from the potentiometer became unreliable, causing the Y-axis to move in unintended directions—often forcing the mechanism into the base instead of the intended travel direction. This was not only difficult to identify as the root cause, but also proved time-consuming to resolve. It highlighted the importance of a stable and unified ground reference throughout the system, especially when dealing with analog signals and position-sensitive components.

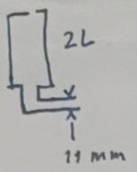
# Pressure Tank Report

This report provides an explanation of the calculations and measurements related to the range performance of the pressure tank gun currently under development.

# Prerequisite to the report

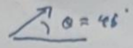
We are developing a water gun designed to achieve a minimum range of six meters. To meet this requirement, a commercial pump has been acquired and is currently being tested by Tolga and Nikita. In parallel, we are exploring alternative propulsion methods, including a reverse bottle rocket concept, where the bottle remains stationary while the water is expelled.

Our target is to pressurize the bottles to 50 PSI, which, based on Radu's calculations, would result in an estimated exit velocity of 22 m/s. These calculations can be found below:




50 psl

$P = \frac{F}{A}$




$F = P \times A$

~~50 PSI ≈ 344738 P~~

~~$A \approx 0.099^2 \times \pi$~~

~~$A \approx 0.031\ m^2$~~

~~$F \approx 10615\ N$~~

time to open and close
100 ms

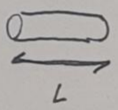
$$v_{exit} = \sqrt{\frac{2 \times (P_{air} - P_{atm})}{\text{Density of water}}}$$

$$v_{exit} = \sqrt{\frac{2 \times (344738 - 100000)}{1000}}$$

$v_{exit} \approx 22\ \frac{m}{s}$

## Drag

To calculate the jet of warter we use the drag coeficient of a cilinder.




↕ D

Diameter = the nosle of the valve

Length = distance traveled by the water before the valve closes back

(we expect to open and close the valve in 100 ms)

$L = 22 \times 0.1$

$L = 2.2$

$D = 0.099$

$A = 0.099^2 \times \pi$

$A = 0.031\ m^2$

Drag coeficient of a cylinder = 0.82

$$D = Cd \times \frac{\rho \times v^2 \times A}{2}$$

$$D = 0.82 \times \frac{1000 \times 22^2 \times 0.031}{2}$$

$D = 6179\ N$ (initially)

$F = m \times a$

$\frac{F}{m} = a$

$a = -90.7\ \frac{m}{s^2}$

**x axis**

$S_x = S_{0x} + v_{0x} \times t$

$S_x = v \times \cos(45) \times t$

$S_x = 15.6 \times t$

$S_x = 15.6 \times 3.19$

$\boxed{S_x = 49.9\ m}$

**y axis**

$S_y = S_{0y} + v_{0y} \times t - \frac{1}{2} \times g \times t^2$

$S_y = v_0 \times \sin(45) \times t - \frac{g}{2} \times t^2$

$0 = 15.6 \times t - 4.91 \times t^2$

$$t = \frac{-b \pm \sqrt{b^2 - 4 \times a \times c}}{2 \times a}$$

$t = 0\ ,\ 3.19\ s$

## First and second try

In our initial attempt, we constructed the system similarly to a conventional bottle rocket, where components such as the valve and the one-way pressurization valve were glued directly to the bottle.

Below are images of the setup, along with a brief explanation of why this approach was unsuccessful:

The concept was sound, but the execution revealed some issues. The assembly was able to withstand pressure up to approximately 10 PSI; however, beyond that point, the glue securing the release valve failed, causing it to detach from the cap.

This failure occurred because the adhesive does not bond effectively to "fatty plastics" such as polypropylene (PP), which was used for the valve components. In contrast, polyethylene terephthalate (PET), which makes up the main body of the bottle, is not considered a fatty plastic and allowed for a stronger adhesive bond. As a result, the one-way valve held securely, while the release valve did not.

To address this issue, we redesigned the system so that all glued components were attached only to the PET bottle material. The revised design is shown below:

This revised approach showed slight improvement, managing to withstand up to 12 PSI before the glue once again failed, resulting in a sudden release of water. While this was a step forward, it remained far from a reliable solution.

To explore more robust alternatives, we began brainstorming unconventional solutions. One idea involved fabricating a custom steel pressure tank through welding. However, commercially available steel tanks were generally too heavy-often exceeding our 11 kg weight limit-and featured unnecessarily large capacities for our intended use.

As a result, we began investigating alternative types of pressure tanks:

# Pressure tanks made from PVC pipe.

We drew inspiration from a variety of sources, focusing in particular on projects where others had successfully stored between 80 and 120 PSI in air cannons-systems with designs conceptually similar to our own. These examples provided valuable insights into feasible construction methods and material choices.

The primary reference we followed was a YouTube video that served as a practical guide for our design approach, which can be found here:


https://www.youtube.com/watch?v=NvH9WHNxvj8

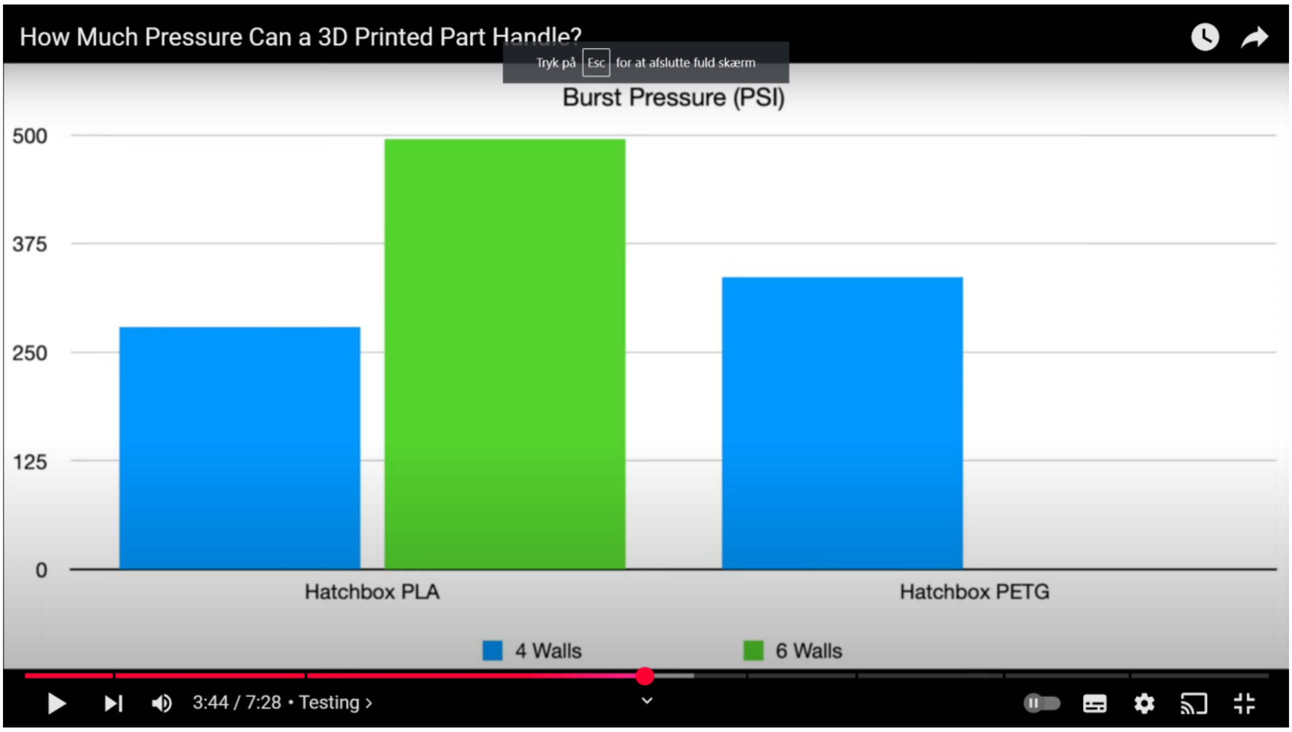
Unfortunately, we were unable to construct this type of pressure tank before identifying new and potentially more effective design alternatives. Additionally, due to the university's strict safety regulations-particularly those concerning the use of pressurized components-we were not permitted to glue end caps onto the pressure tubes, as this posed a risk of failure and potential injury.

As a result, we decided to continue exploring alternative solutions that align with both our performance requirements and safety constraints.

## 3D printed tank

Initially, we did not believe a 3D-printed pressure tank would be a viable option. In general, 3D-printed components are not considered watertight-or gas-tight-due to the presence of small gaps and layer imperfections inherent in the printing process. As a result, we dismissed this solution early on.

However, our perspective changed after discovering the following video, which demonstrated a successful implementation of a functional 3D-printed pressure vessel:




https://www.youtube.com/watch?v=ZB6VbkeYrkw

The video demonstrated that there is indeed significant potential for a 3D-printed pressure vessel to function effectively. However, one of the key limitations highlighted in the project was the inability to achieve a fully leak-proof design.

Based on these findings, we began investigating alternative methods and materials that could address this issue while still allowing us to pursue the 3D-printed tank concept.


The video showcased a similar pressure tank design that achieved a leak-free seal and was fabricated using ABS plastic rather than PLA. The tank was also vapor-smoothed with acetone to improve surface integrity and sealing. While vapor smoothing using a controlled acetone chamber is not feasible within school facilities, a more practical approach-brushing acetone directly onto the surface-appears to be a workable alternative.

To evaluate this approach, we began by printing a small-scale prototype. Tobias 3D printed the initial model using his personal printer and mounted the necessary components, including a one-way valve and a release valve. Despite noticeable leakage, the design was able to hold pressure up to 100 PSI. Further testing beyond this point was avoided for safety reasons.

Following this initial success, we chose to print an improved version with increased structural integrity. The original print featured only two outer walls, a 30% infill, and two inner walls, which left us with limited confidence in its durability during higher-pressure testing. To address this, we reprinted the tank with a total of twelve perimeters (walls), greatly enhancing its ability to withstand internal pressure and improving its watertightness.

Although we do not believe twelve walls will be necessary for the final design-based on references from YouTube demonstrations showing sufficient performance with as few as four to six walls-we opted for a highly reinforced version during the testing phase. The rationale behind this decision was to prevent premature leaks or structural failures before implementing a proper safety valve system. This safety valve will be essential for releasing pressure in case it exceeds the design threshold. Until such a system is integrated, it is important to maintain a conservative design with a sufficient number of walls to ensure safe and reliable pressure testing

## Introduction of Barometer

For the final product, our goal is to reproduce a consistent internal pressure without relying on visual inspection of the compressor's built-in barometer, as this would require manual intervention. To automate and monitor the system more effectively, we aim to integrate a pressure sensor (barometer) directly into the tank.

Incorporating electronics into a sealed pressure vessel presents a significant challenge, particularly in maintaining structural integrity while allowing for electrical wiring. Wireless solutions were considered, but due to concerns regarding their reliability-especially in critical testing or demonstration scenarios-we opted for a wired approach to ensure consistent performance.

To accommodate this, we have designed a small square access port in the tank wall, which can be sealed using a removable end cap. The cap is secured with eight M3 bolts, each providing a theoretical pullout strength of 1304 N per thread. This configuration is intended to maintain a tight seal under pressure while still allowing for sensor installation and wire routing in a controlled and serviceable manner.

$1304 \cdot 8$

$$10432$$

maximum amount of pressure the 8 screws can theoritically hold

$30 \cdot 30$

$$900$$

the area that the inner square of our thing is.

$\frac{10432}{900}$

$$\frac{2608}{225}$$

$\xrightarrow{\text{at 5 digits}}$

$$11.591$$

the is the maximum $\frac{N}{mm^2}$ that our little pressure plate can hold before it rips out the threads. This is ofc not taking into account bending from the plastic, material probaties or anything else.

Based on the calculated pullout strength of the threaded inserts, the lid assembly is theoretically capable of withstanding internal pressures exceeding 1600 PSI. This high pressure capacity is due to the use of threaded heat-set inserts in the PLA body, which offer significantly better thread strength and reusability compared to directly 3D printed threads. These inserts allow the cap to be securely mounted and removed repeatedly without degrading the structural integrity of the connection.

However, it is important to note that while the calculated values suggest high mechanical resilience, the actual performance is limited by the material properties of the lid itself. Since the lid is printed in plastic, it is likely to deform or fail well before reaching the theoretical pressure limit. Nonetheless, these calculations provide a useful theoretical baseline, indicating that the overall design is likely sufficient for our target operating range.

To achieve a proper seal between the cap and the pressure vessel, we plan to manufacture a custom 3D-printed gasket using TPU (thermoplastic polyurethane). Fortunately, TPU filament is available for in-house use, allowing immediate production without reliance on the university's 3D printing lab schedule.

This "lid gasket," as we will refer to it moving forward, will initially be printed using standard 80A TPU, which is one of the softest commercially available grades. In parallel, we have also requested assistance from Olga-who specializes in advanced 3D printing workflows-to fabricate a version using a silicone-like pellet-based material available in the university's lab, which may offer improved sealing properties.

For the lid material, we intend to transition from PLA to PETG reinforced with carbon fiber. This material offers increased stiffness, which is essential to prevent bending or deformation in areas not supported by bolts. However, we will continue initial tests using PLA, particularly in fully dense (100% infill) configurations, before making final material decisions based on actual performance data.

Ultimately, this design iteration proved unsuccessful. The following section provides a detailed breakdown of its shortcomings:

## Barometer

Initially, the pressure sensor appeared suitable for our application, as the specification sheet listed a pressure range from 0 to 1100 MPa. This would have far exceeded our operational requirements. However, upon closer inspection, it became clear that the unit was in fact specified in hectopascals (hPa), not megapascals (MPa). This meant the sensor's actual maximum measurable pressure was approximately 1100 hPa, or roughly 15.9 PSI.

Given that this value falls well below the pressures we intend to operate with, the sensor was deemed unsuitable for our design. As a result, we decided to abandon the use of an electronic pressure sensor altogether and instead rely on a mechanical pressure relief valve to regulate internal pressure.

This shift in approach later proved to be beneficial, particularly when working with compressed air systems, where pressure control and fail-safety are critical.

## New Barometer

During the development of the pressure tank system, we originally intended to use the MS5837-07BA pressure sensor from TE Connectivity. This sensor was a strong candidate for our project due to its small physical footprint, high precision, and ability to operate reliably in wet environments. It supports digital communication via I2C and offers a pressure range from 0 to 7 bar, making it suitable for the expected operating conditions of our system.[1]

The MS5837-07BA also features a 24-bit ADC, internal temperature compensation, and comes factory calibrated, which would have made integration straightforward and saved valuable development time. Its construction includes a gel-filled stainless steel cap, giving it water resistance and improved durability in demanding environments. For our application, it would have provided a compact and accurate solution for continuous pressure monitoring without relying on manual readings.[2]

However, due to delays in shipping, we did not receive the sensor in time to include it in the current build. As a result, we chose to proceed with a mechanical pressure relief valve to regulate system pressure. While this approach is less advanced in terms of measurement capability, it allowed us to continue development without risking overpressure during testing. The MS5837-07BA remains a strong

[1] https://www.mouser.dk/ProductDetail/Measurement-Specialties/20005303-00?qs=TiOZkKH1s2SLHg%2FmYB3xKw%3D%3D&srsltid=AfmBOoreWA-uy3jpXGyAwQ5W7rw83dwxolGVxAsPU6jETuTnj9hm4m9J
[2] https://www.mouser.dk/datasheet/2/418/5/ENG_DS_MS5837_07BA_A-1955840.pdf

option for future iterations of the project, where better timing and availability could allow for more advanced sensing and control features.

### Tank lid design

In the end, introducing a hole into the pressure tank presents a significant compromise in both safety and long-term reliability. While certain commercial pressure vessels are designed with lids or integrated sealing mechanisms, maintaining a completely sealed structure is generally preferable for sustained performance and structural integrity.

For this reason, we concluded that embedding a pressure sensor directly inside the tank is not the optimal solution. Instead, a more reliable and modular approach involves integrating the pressure reading system into the outlet assembly, specifically within the 1/2-inch tube fitting system. This configuration eliminates the need to modify or reprint the pressure vessel for each revision and allows for greater adaptability across different testing scenarios and use cases.

This modular strategy not only simplifies the overall design and reduces failure points but also enables easier maintenance and customization without compromising the structural integrity of the tank itself.

## Redesign to be better to 3D print.

To improve reliability and reduce the risk of failed prints, we decided to redesign the 3D-printed pressure tank. In earlier versions, print interruptions or instability in vertical walls led to structural weaknesses and incomplete parts. To address this, the new design features inward-facing walls slanted at a 45-degree angle. This angled geometry provides better support during the printing process and helps prevent the upper layers from collapsing or shifting, especially when printing without additional support material.

As a result of the new slanted wall design, the pressure tank naturally developed slightly thicker sections near the internal corners. While this does reduce the internal volume of the vessel to a small degree, it does not significantly affect the structural strength or integrity of the tank. Given that our primary focus was on achieving a reliable and repeatable print, this trade-off was considered acceptable.

We did not anticipate any negative impact from this change and proceeded with the revised design. The updated version was successfully printed without any major issues or failures. Following the successful fabrication, we moved on to calculating the maximum internal pressure the vessel could safely withstand.

# Calculating Maximum pressure

**4.1 Maximum Internal Pressure Estimation Based on Material Strength**

To determine the safe working pressure of the cylindrical vessel, we apply classical thin-walled pressure vessel theory. The objective is to identify the maximum internal pressure the structure can withstand without exceeding the material's tensile strength, accounting for anisotropic mechanical properties introduced by the 3D printing process.

**Geometrical Parameters:**

- Inner radius: r = 90 mm = 0.09 m

- Wall thickness: t = 5 mm = 0.005 m

**4.1.1 Hoop Stress (Circumferential Direction – XY Plane)**

The hoop stress represents the stress experienced along the circumference of the cylindrical wall due to internal pressure. For a thin-walled vessel, it is given by:

$\sigma_h = (P \times r) / t \rightarrow P = (\sigma_h \times t) / r$

Assuming the printed material achieves a tensile strength of approximately 50 MPa in the XY (hoop) direction:

$P = (50 \times 10^6 \times 0.005) / 0.09 = 2.78 \times 10^6$ Pa = 2.78 MPa

This corresponds to an approximate internal pressure of 2.78 MPa, or 403 PSI. This value represents the theoretical maximum pressure before failure due to hoop stress.

**4.1.2 Longitudinal Stress (Z Axis – Layer Direction)**

Due to the layer-by-layer nature of additive manufacturing, tensile strength in the Z direction is significantly reduced compared to the XY plane. For safety and based on empirical estimates, the tensile strength along the Z axis is assumed to be approximately 15 MPa.

The longitudinal stress for a cylindrical pressure vessel is given by:

$\sigma_l = (P \times r) / (2 \times t) \rightarrow P = (2 \times \sigma_l \times t) / r$

$P = (2 \times 15 \times 10^6 \times 0.005) / 0.09 = 1.67 \times 10^6$ Pa = 1.67 MPa

This corresponds to approximately 1.67 MPa, or 242 PSI.

**Conclusion**

While the circumferential (hoop) stress limit suggests a maximum pressure of 2.78 MPa, the more critical failure mode lies along the longitudinal axis due to reduced tensile strength in the Z direction.

Therefore, the safe maximum internal pressure for this vessel should be considered as 1.67 MPa, unless post-processing or reinforcement is used to improve layer adhesion strength.

As we will not go over the safety limit of 9Bar or 0.9MPa, this would be okay, and we can now go ahead with more testing.

## Setting up a test bench

After successfully producing a functional and reliable pressure vessel, the next step was to design a method for introducing and releasing pressure from the system. Introducing pressure proved to be relatively straightforward. We selected a standard one-way valve commonly used for car tires due to its affordability, simple design, and relatively high pressure tolerance-typically up to 8 bar when using higher-quality variants. Its installation is also simple, requiring only a 12.5 mm hole in the vessel wall, making it an obvious and efficient choice for pressurization.

For the outlet side, we integrated a 1/2-inch threaded insert into the pressure vessel. This allowed compatibility with standard plumbing fittings, significantly reducing the cost of testing components and enabling a modular setup. This standardization was especially beneficial in terms of integrating an electrically operated magnetic solenoid valve, which replaced the need for a manual ball valve. The solenoid valve provides better control and enables remote activation of the system.

The threaded outlet connects directly to a T-fitting, which serves as the central hub for three key components: the pressure tank, the pressure relief (safety) valve, and the exhaust solenoid valve. This setup allows for pressure to be safely regulated, contained, and released in a controlled manner, supporting both safe operation and efficient testing.

The safety valve proved to be one of the more challenging components to integrate into the system. Most off-the-shelf safety valves are designed to vent pressure directly to the surrounding environment when triggered. While this is functionally acceptable, it presented a specific issue in our setup: the valve includes an O-ring for water sealing, and we did not want pressurized air or fluid to forcefully eject the O-ring during venting. This could not only damage the valve but also pose a safety risk.

To mitigate this, we temporarily connected a manual ball valve to the outlet side of the safety valve. This allows controlled venting when necessary and prevents unwanted ejection of components. However, this approach introduces a serious limitation: **if the ball valve remains closed at the moment venting is required, the safety valve will not be able to perform its function. This could lead to dangerous pressure buildup inside the vessel. As such, this design is not safe to rely on in long-term use or in situations where consistent operator awareness cannot be guaranteed.**

If this prototype were to be developed into a final product, the safety system would need to be redesigned to ensure fully automatic and fail-safe pressure release. **Relying on manual operation introduces unnecessary risk and is not appropriate for repeated or unsupervised use.**

For now, as this remains an early-stage prototype, the current setup is considered sufficient. It allows us to perform necessary tests while staying within our project's time and resource constraints. The safety valve and ball valve have not been included in the final CAD model due to time limitations, but the rest of the system has been modeled, and the overall assembly layout is shown in the figure below.


Using simple plumbing fittings and pipe will decrease the fluid flow through the pressure tank assembly, but just using more pressure would eliminate this issue.

Using this assembly, we managed to get some very good results, more than what was expected from the calculations.

Shooting over 11meters at just 4.5 Bar

And over 15meters at 7bar. This shows a huge improvement over the bought pump that we have.

There is going to be more about this in the later stage of this report.

# Compressor attachment

To pressurize the chamber, we chose to use a standard 12V compressor typically used for inflating car tires. This type of compressor was selected due to its affordability, reliability, and ease of disassembly. Internally, it consists of a compact compressor housing with a small piston mechanism that draws in ambient air and compresses it. The compressed air is then delivered through a flexible hose, which connects directly to the one-way valve mounted on the pressure chamber. This setup provided a simple and effective solution for generating the required air pressure during testing.

# Solenoid valve

Using a magnetic solenoid valve was an obvious choice when designing the mechanism for releasing pressure from the vessel. With the ability to withstand pressures up to 8 bar before activation, it was well-suited to our system. In addition, its fast response time-capable of opening within approximately 70 milliseconds-made it ideal for controlled and repeatable operation.[3]

This rapid electronic actuation was essential to our design, as it allowed the system to be triggered without manual intervention. The solenoid valve enables precise timing and remote control, which would not be possible with a manual ball valve.

[3] https://arduinotech.dk/shop/solenoid-valve-ac-230v-1-2-straight/?gad_source=1&gad_campaignid=17511696673&gbraid=0AAAAAChom3Jaqqyofl5brNB6STwELL04U&gclid=CjwKCAjw6NrBBhB6EiwAvnT_rtRIVN6sK6QK9cvjskwokkuCdEWLZz-hn5uBruKO0-uubJwwaEApxhoCodEQAvD_BwE

From an implementation standpoint, the solenoid valve is straightforward to use. It only requires a standard 12V DC input (or the rated voltage specified in the datasheet) to activate the magnetic coil, causing the internal mechanism to open and allowing water or air to flow through. This made it a reliable and easy-to-integrate component for the firing mechanism of the pressure system.

## Relay control

To control the solenoid valve electronically, we used a 2-channel relay module designed for use with microcontrollers such as the Arduino. This module allows for simple switching of high-power components using low-voltage digital signals. It was an obvious choice, as it enables safe and isolated control of the 12V solenoid valve using the 5V output from the Arduino.[4]

The relay module includes built-in optocouplers, which provide electrical isolation between the control logic and the high-power switching side. This is especially important when dealing with inductive loads like solenoid valves, where voltage spikes can damage sensitive electronics. By using this module, we avoid the need to design custom switching circuitry, making the setup both safer and more reliable.

Each relay is rated to handle up to 10A at 250V AC or 10A at 30V DC[5], which is far beyond the requirements for our valve. It also includes indicator LEDs for each channel, giving quick visual feedback when a relay is active. These features make the module ideal for prototyping and testing under tight time constraints.

In our setup, the relay module receives a signal from the Arduino, which then opens or closes the circuit to the solenoid valve depending on the firing sequence. While this is a relatively simple solution, it adds a level of control and safety that would be difficult to achieve manually.

## Pictures and testing

With all major components assembled, we were able to complete the construction of the final version of the pressure vessel-based launcher. The following section includes images of the finished setup, as well as a brief overview of the initial testing procedures.

Although the system was designed to be controlled via the Arduino and relay module, the first round of testing was conducted using a simplified setup. Instead of using the relay board, we directly triggered the solenoid valve using a 12V power supply. This power was provided by the 12V PD (Power Delivery) board that had previously been purchased for charging the system's battery and supporting the onboard power distribution.

This direct connection allowed us to validate the basic functionality of the solenoid valve and ensure the entire system could operate safely under pressure before introducing more advanced electronic control logic.

[4] https://www.handsontec.com/dataspecs/2Ch-relay.pdf
[5] https://www.handsontec.com/dataspecs/2Ch-relay.pdf

The following images show the testing setup, where the pressure tank was evaluated in combination with the solenoid valve and an external air compressor. This test proved highly successful. At a pressure of just 4.5 bar, the system achieved a firing range of approximately 11 meters. When pressurized to 7 bar, it reached an impressive distance of 15 meters.

These results confirm that the core concept is functional and capable of delivering the required performance. The pressure vessel, valve system, and launch mechanism worked together effectively, validating the design under real test conditions.

The image below shows the system in operation during a live firing test. A relatively uniform stream can be seen exiting the nozzle, indicating that the internal pressure was sufficient to provide a consistent and focused output. This supports the conclusion that, despite minor leakage, the system is capable of functioning as intended under test conditions.

The only significant failure observed during testing was the gradual leakage of the pressure vessel. During pressurization, visible signs of leakage-often referred to as "sweating"-were noticed along the printed layers of the tank. While this was not an immediate structural failure, it did indicate the presence of microscopic pinholes or gaps within the printed walls. These are likely caused by the limitations of FDM printing, where layer adhesion may not be perfect throughout the entire structure. As a result, when the vessel is pressurized, small amounts of water and air are forced through these pores, gradually reducing the internal pressure.

Although the leaking appeared concerning, especially visually, it did not present any immediate danger of catastrophic failure during our testing. The vessel maintained its shape and did not show signs of cracking or delamination under pressure.

The video guide we referenced during development mentioned this issue as a known limitation when the print is not vapor smoothed. Unfortunately, due to safety restrictions imposed by the university, we were not allowed to perform vapor smoothing using an acetone chamber. As a result, we proceeded with the understanding that minor leakage was an acceptable compromise for this prototype stage. While not ideal, it allowed us to complete functional testing of the system under relatively safe conditions.

# Conclusion

This project set out to design and build a functional pressure-based water launcher capable of reaching a minimum range of six meters. While the original plan was to use a commercially available pump, it quickly became clear that building a custom pressure vessel would offer both greater flexibility and better performance. In the end, this approach proved to be the correct choice. Not only was it the more correct engineering way, but it also allowed for more precise control over the system's output and design parameters.

From a **mechanical perspective**, the custom 3D-printed pressure vessel demonstrated sufficient structural integrity for testing purposes. Through iterative design improvements-such as the use of slanted internal walls, increased perimeter thickness, and modular fittings-the final prototype was able to safely contain and release pressurized air. While minor leakage through the printed layers occurred, the vessel did not fail structurally and successfully operated at pressures up to 7 bar. The modular connection system using 1/2-inch plumbing fittings further improved the practicality and reliability of the design.

The **electrical system** was kept simple and effective. Although the final tests did not incorporate the Arduino-based relay control system, the solenoid valve was successfully triggered using a 12V PD board. This demonstrated that the system could be upgraded with electronic control in future iterations, enabling more advanced firing logic and integration into a larger automated setup. The use of standard relay modules and easily accessible components supports ease of maintenance and further development.

From a **mathematical and performance standpoint**, the prototype exceeded initial expectations. With only 4.5 bar of pressure, the system achieved an 11-meter firing distance-nearly doubling the original design goal. At 7 bar, it reached up to 15 meters. These results validate the pressure and velocity calculations made earlier in the process and show that the design can be tuned further depending on application needs.

Overall, the decision to design and build a custom pressure vessel system proved to be the correct approach. It allowed for better performance, lower cost, and greater adaptability than any commercial pump could have provided. Despite time constraints and minor technical setbacks, the project demonstrates a successful balance of mechanical design, electrical integration, and mathematical validation, resulting in a fully functional and testable prototype