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Storage of Hydrogen in Pressure Vessels for Military Vehicles

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Abstract

This report explores the feasibility of retrofitting the Boxer armoured vehicle with hydrogen power, focusing on material science and manufacturing techniques. Key materials include aluminium alloy liners for hydrogen storage, Carbon Fibre Reinforced Polymer for reinforcement, and Kevlar for impact resistance. Advanced processes such as rotational moulding and filament winding ensure lightweight, high-strength storage systems suitable for military demands.

Fuel cells are identified as the superior propulsion option due to their efficiency and low emissions, despite higher costs. While hydrogen integration involves significant upfront investment, it offers long-term benefits in safety, durability, and sustainability. This study concludes that hydrogen-powered military vehicles like the Boxer can meet future operational and environmental standards.

Abbreviations

BCC	Body-Centred Cubic
BEV	Battery Electric Vehicle
CFRP	Carbon Fibre Reinforced Polymer
COSHH	Control of Substances Hazardous to Health
FCC	Face-Centred Cubic
FCEV	Fuel Cell Electric Vehicle
FSW	Friction Stir Welding
HE	Hydrogen Embrittlement
HGV	Heavy Goods Vehicle
H2-ICE	Hydrogen Internal Combustion Engine
NDT	Non-Destructive Testing
PA	Polyamide
PRD	Pressure Relief Device
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

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1. Introduction

This report will explore a selection of materials suitable for a hydrogen-powered military vehicle, aiming to develop a concept that meets the rigorous demands of military operations while producing zero air emissions. Manufacturing processes will also be explored with a cost analysis to complete the report. The vehicle must match or exceed the efficiency of existing vehicles to be a practical alternative, with the added challenge of the inherent weight of military vehicles due to armour and weaponry. As fuel costs are one of the military's largest expenditures, transitioning to hydrogen-powered vehicles presents an opportunity for significant savings. However, achieving sufficient power and fuel performance will require research into advanced technologies beyond those used in conventional commercial hydrogen vehicles. Additionally, the vehicle must be designed to operate in high-conflict environments and incorporate appropriate levels of armour for protection [1].

Transportation contributes approximately 30% of global carbon emissions, with 72% of these emissions originating from road transport, including cars, vans, lorries, and buses. In recent years, global leaders have prioritised renewable energy development to address climate change. Electric vehicles (EVs) have gained significant traction as a zero-emissions option, supported by government incentives such as subsidies and grants. However, EVs face challenges with long charging times, making them less suitable for military applications [2] [3].

2. Background and research

To narrow the focus of this report, a specific military vehicle has been selected for comparison and detailed research. This section will provide background information on both the chosen vehicle and hydrogen-powered vehicles.

2.1 Vehicle

Various options were considered, with a multi-purpose armoured fighting vehicle being superior. An alternative idea involved converting a military transport vehicle, such as the Land Rover Wolf, into a hydrogen-powered model. However, this approach posed less of a challenge. Therefore, the British Army's "Boxer" [Fig.1] was selected as the focus of this report.



Figure 1 - British Army Boxer 8x8

2.1.1 Powertrain

The 38.5 Tonne Boxer is an 8x8 armoured vehicle designed for rapidly transporting soldiers. Featuring two power variants, a Rolls-Royce MTU 8V 199 TE21 and a TE20 diesel engine. The TE21 shares identical core specifications but offers enhanced output capabilities with a higher power of 600 kW (816 hp) compared to the TE20's 530 kW (721 hp) and greater maximum torque at 3000 Nm (2212 ft-lbs) versus 2700 Nm (1991 ft-lbs) [4] [5].

2.1.2 Range

The Boxer boasts an impressive range of approximately 684 miles but achieves poor fuel efficiency at only 0.8 to 1.2 mpg, reflecting the trade-offs in military vehicle design. Heavy weight, protection requirements, and complex engineering prioritise operational capability over fuel efficiency. The average range for multi-purpose armoured vehicles, including the Boxer's counterparts like the 8x8 Bumerang and ZBL-09, is around 500 miles. For retrofitting with hydrogen power, a target range of 450 miles is reasonable, applying a 10% fiddle factor for any discrepancies [6].

British Army vehicles generally achieve slightly better fuel efficiency than their US counterparts but remain far from eco-friendly. For example, the Challenger 2 tank consumes around 0.6 mpg, compared to the M1 Abrams at 0.5 mpg, while the Stryker, the US equivalent of the Boxer, achieves 1.2 mpg. Lighter vehicles like the Foxhound reach 8–10 mpg, and the Land Rover Wolf exceeds 20 mpg on-road, though fuel economy drops significantly in harsh terrain or operational conditions.

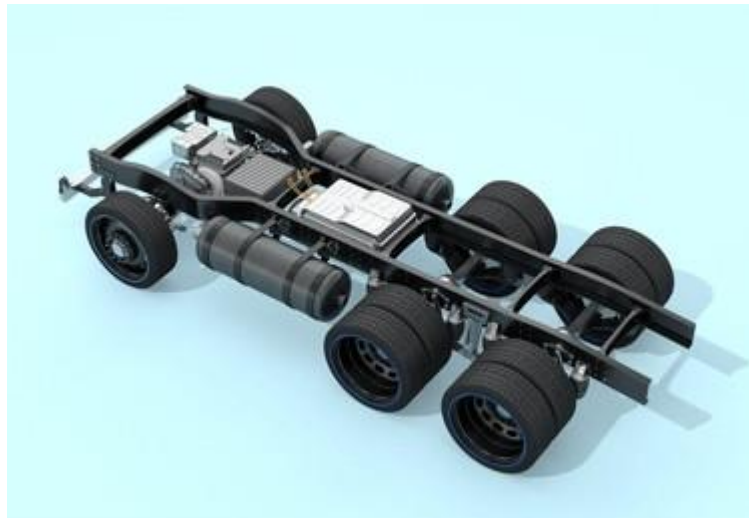


Figure 2 - Hydrogen Vehicle Chassis

A study by Consumer Reports found that Electric Vehicles (EVs) often fall short of advertised range estimates due to real-world factors like temperature, driving habits, and terrain. Tested under ideal Worldwide Harmonised Light Vehicle Test Procedure conditions for marketing, EVs struggle in colder temperatures as batteries become less efficient, reducing range. In contrast, hydrogen vehicles show greater resilience.

Toyota faced criticism for overstating EV range, highlighting a common issue of exaggerated claims in the EV market [7].



Figure 3 - Hydrogen Tank Concept

Using hydrogen in heavy vehicles, such as military and Heavy Goods Vehicles (HGVs), is not a new concept, with extensive research available online. Adopting hydrogen technology in HGVs would significantly reduce global emissions. HVS, a UK-based hydrogen HGV start-up, recently unveiled its 40-tonne HGV [Fig.4] technology demonstrator, featuring a unique powertrain and innovative cab design. The HVS boasts an impressive range of 370 miles (600 kilometres) using this method which the Boxer could be compared to. The British Army's Boxer has a gross vehicle weight (GVW) of 38.5 tonnes, increasing to 41 tonnes with payloads. For this assignment, the weight is assumed to be 38.5 tonnes [8] [9] [10].



Figure 4 - HVS Concept

2.2 Hydrogen

Hydrogen, the simplest and most abundant element, consists of a single proton, while its isotopes, deuterium and tritium, have one and two neutrons, respectively. Deuterium has a slightly higher energy density than regular hydrogen, but using it in hydrogen fuel cells, especially for vehicles, is impractical due to high costs and infrastructure designed for regular hydrogen. Despite its marginal energy advantage, hydrogen remains the optimal choice for this military vehicle [9].

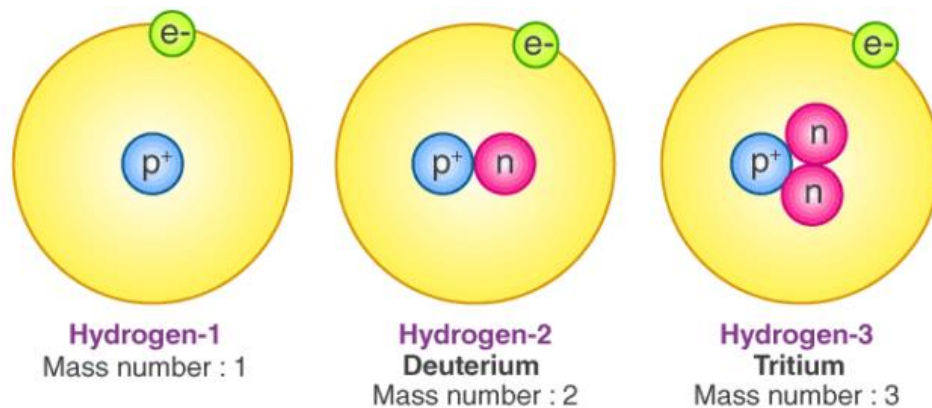


Figure 5 - Isotopes of Hydrogen

95% of global hydrogen production relies on Steam Methane Reforming, which emits 9–12 kg of CO₂ per kilogram of hydrogen produced. However, this CO₂ can be captured and prevented from entering the atmosphere. This process makes hydrogen a more environmentally friendly energy source and stronger candidate for military applications requiring high performance and efficiency.

2.2.1 Hydrogen Vehicles

Hydrogen-powered vehicles come in two main types: Fuel Cell Electric Vehicles (FCEVs) and hydrogen combustion engines. FCEVs use a fuel cell to convert hydrogen and oxygen into electricity through reverse electrolysis [Fig.6], storing the energy in a lithium battery to power an electric motor.

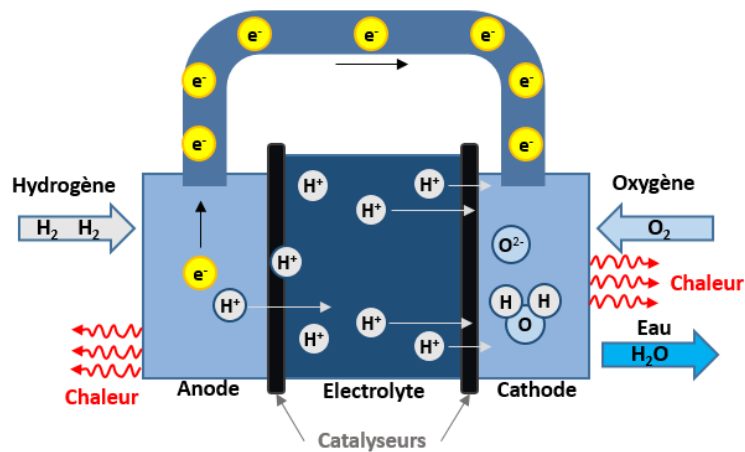


Figure 6 - Reverse Electrolysis

This process produces only water vapour as a byproduct, resulting in zero harmful emissions. In contrast, hydrogen combustion engines burn hydrogen instead of petrol or diesel to generate power. Unlike Battery Electric Vehicles (BEVs), which rely solely on rechargeable batteries, FCEVs function as onboard power plants, generating electricity without external charging.

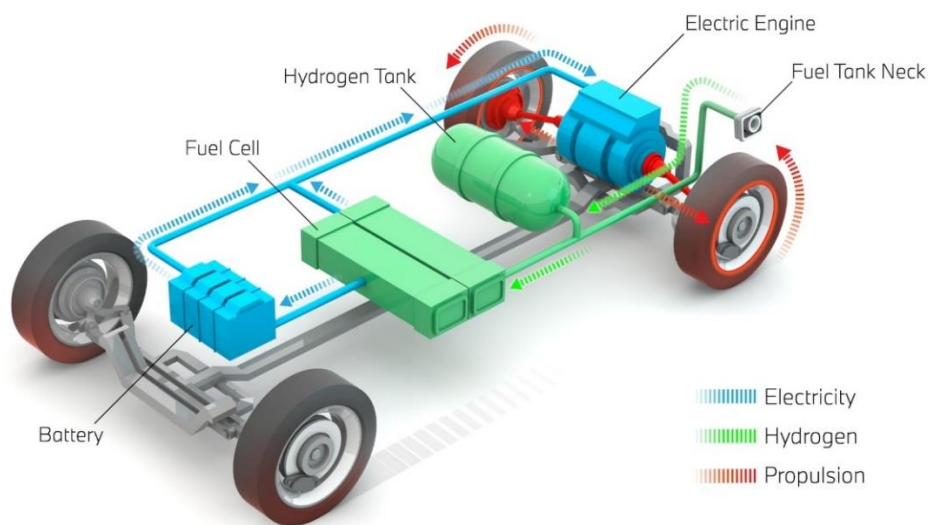


Figure 7 - How a Hydrogen Vehicle Works

Fuel cells in hydrogen vehicles distribute electricity based on driving needs, either powering the motor directly or charging a small buffer battery for temporary energy storage. The buffer battery, smaller and lighter than those in fully electric vehicles, is continually recharged by the fuel cell, ensuring a constant energy supply for efficient, emission-free performance [11].

Converting the Boxer to hydrogen power requires a solution that balances durability, efficiency, and cost. While hydrogen combustion engines are robust, easy to integrate, and field-maintainable, they are less efficient and consume more hydrogen than fuel cells, making them less optimal for space-limited and long-term sustainability needs. In contrast, hydrogen fuel cells are highly efficient, converting more energy into power with zero operational emissions. Although fuel cells are more costly and require careful maintenance, their superior efficiency and range make them the better choice for military operations, especially for missions where stealth and fuel economy are priorities [12].

2.2.2 Hydrogen Storage

Hydrogen, the lightest element, easily permeates materials and is stored at high pressures of up to 700 bar in modern hydrogen vessels. These vessels typically consist of an inner liner made of or aluminium, surrounded by layers of Carbon Fibre Reinforced Plastic (CFRP) applied using Filament Winding (FW) methods. This design is widely used in commercial hydrogen vehicles due to its balance of lightweight properties, strength, and cost-effectiveness [13].

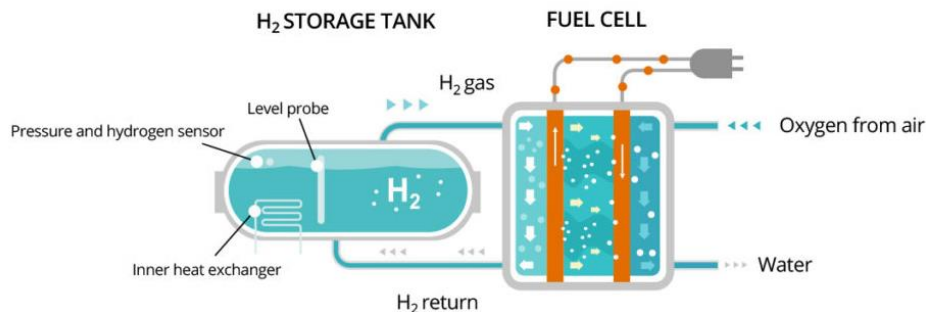


Figure 8 - Hydrogen Storage Process

As the Boxer is a military vehicle, the liner material needs to be carefully considered to enhance protection against battlefield hazards. The CFRP will remain critical in the shell due to its exceptional fracture toughness and lightweight nature. Thickening the CFRP layers is potential approach to increase resilience while maintaining performance in high-pressure hydrogen environments [14].



Figure 9 - Toyota Miria Turned into Hydrogen Bomb

The dangers of hydrogen misuse were demonstrated when Ukrainian forces reportedly converted a Toyota Mirai into a hydrogen bomb with an explosive force of 180 kg of TNT [Fig.9]. This underscores the need for strict safety measures and robust engineering in military applications.

2.2.3 Hydrogen effects on other materials

Hydrogen leakage could pose significant challenges for the Boxer, particularly given its construction of welded steel and its operation in combat zones. If hydrogen were to leak from storage vessels within the vehicle, it could lead to hydrogen embrittlement of the steel components over time, especially under the high pressures and fluctuating temperatures experienced in military environments.

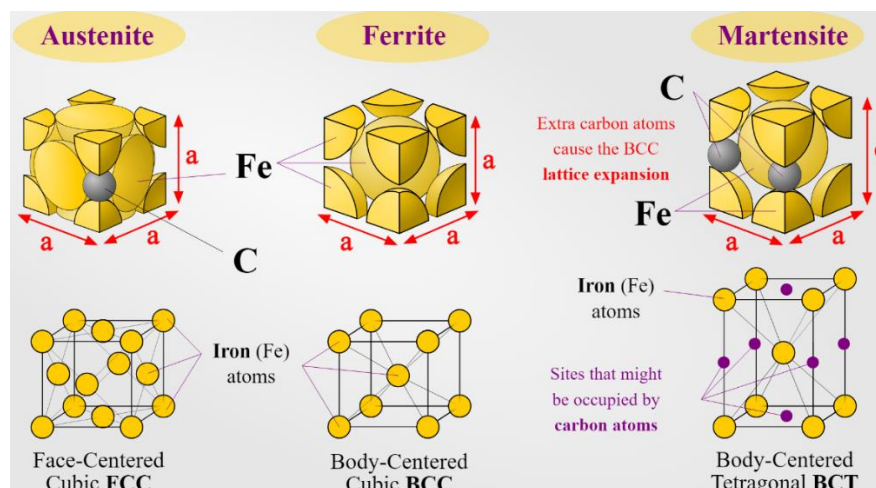


Figure 10 - Material Properties for Hydrogen Resistance

This embrittlement could weaken the vehicle's structural integrity, making it more susceptible to cracking or failure under stress or impact. Ensuring the Boxer's

hydrogen storage systems are leak-proof and that its steel components are designed or treated to resist hydrogen-induced degradation is essential for maintaining its reliability and safety in the field.

2.2.4 Hydrogen-Air Mixture Reaches Explosive Range

If hydrogen escapes from the vessel and accumulates in a confined space, such as under the vehicle, it poses a significant explosion risk within its flammable range. To mitigate this, the vehicle must include a pressure relief system. The Boxer can operate in water up to 1.5 metres [Fig11], requiring a snorkel for the pressure relief system to extract the hydrogen above the water. If the hydrogen vessel is penetrated underwater, the gas will rise to the surface, aiding dispersal. However, if it encounters an ignition source, such as gunfire or electronics, it could ignite, producing a nearly invisible but dangerous flame. In confined spaces above water, hydrogen-air mixtures between 4% and 75% concentration can create explosive hazards, posing serious risks to personnel and equipment [15] [16].



Figure 11 - Boxer in Water

2.2.5 Hydrogen Vessels Required

The Boxer's combat weight of approximately 36 tonnes significantly influences hydrogen consumption, estimated at 7kg per 100 km (62 miles).based on data from fuel cell tractors with consumption rates of 9.2kg/100 km. However, advancements in

technologies, material selection, and improved fuel cell efficiency make it possible to achieve a consumption rate closer to 6.7kg/100 km [17] [18].

To achieve a 450-mile (724 km) range, the Boxer would require approximately 50kg of hydrogen. High-pressure hydrogen vessels, commonly used in such applications, can store around 5 kg of hydrogen per vessel, requiring 10 vessels to meet the desired range [19].

However, using Voith's certified 700-bar hydrogen vessels [Fig.12,13], which can store 7.1 kg of hydrogen each, the Boxer would only require 8 vessels to achieve the same range. These vessels are bigger but would reduce the overall required storage space and weight. These vessels are designed with advanced materials for safety and efficiency, making them an ideal choice for heavy-duty applications like military vehicles [20].



Figure 12 - Carbon4Tank on Truck

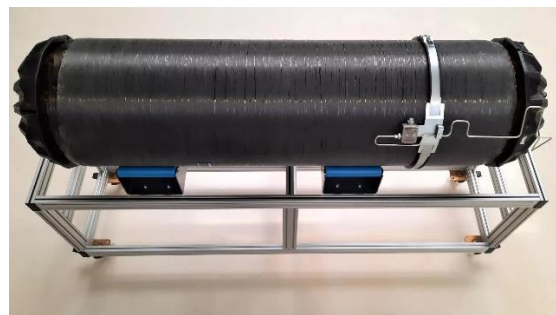


Figure 13 - Carbon4Tank

The hydrogen storage system would add approximately 1,000–1,200 kg to the vehicle, including the weight of the vessels and the stored hydrogen which isn't much in comparison to the weight of the boxer. The vessels must be strategically integrated into the Boxer's modular design to ensure operational functionality, maintain balance, and provide armour protection [21].

2.2.6 Hydrogen Vessel Placement

To safely integrate hydrogen vessels into a Boxer armoured vehicle, the optimal placement would be along the chassis and under the floor structure, with a slight

extension of the wheelbase to accommodate centralised storage between the axles. This configuration lowers the vehicle's centre of gravity, improving stability and ensuring even weight distribution, which is crucial for off-road mobility and rapid manoeuvres.

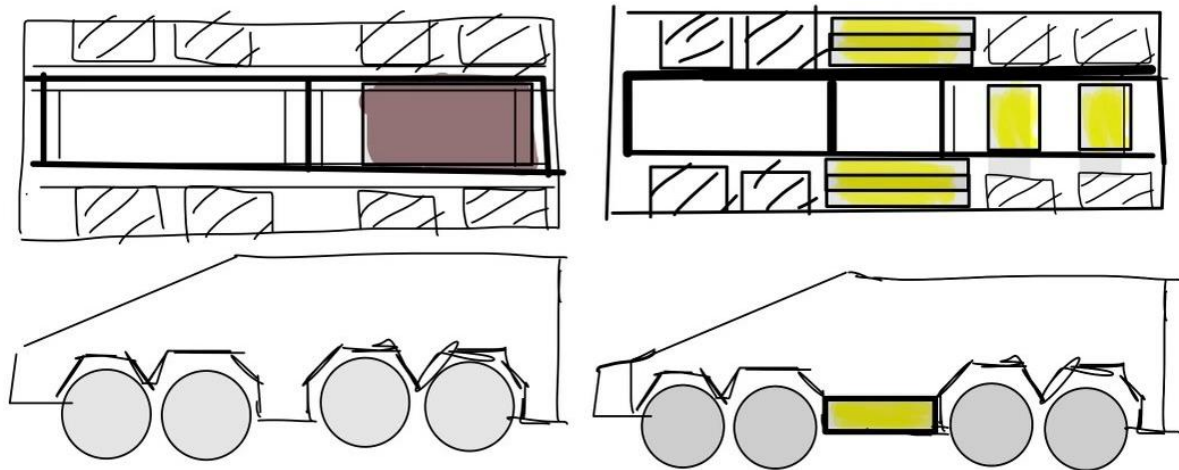


Figure 14 - Drawing of Boxer with Extended Wheel Base

Placing the vessels centrally within the vehicle's core provides maximum protection, as they would be shielded by the surrounding armour from direct impacts. However, ground-level threats such as IEDs could pose a threat, therefore additional blast-resistant shielding, such as composite armour, will be required. This approach takes advantage of the Boxer's modular design, allowing for integration without compromising its primary operational capabilities. Images of the Boxer's chassis are restricted, but Figure 15 shows a similar fuel tank, positioned towards the rear due to its large size.

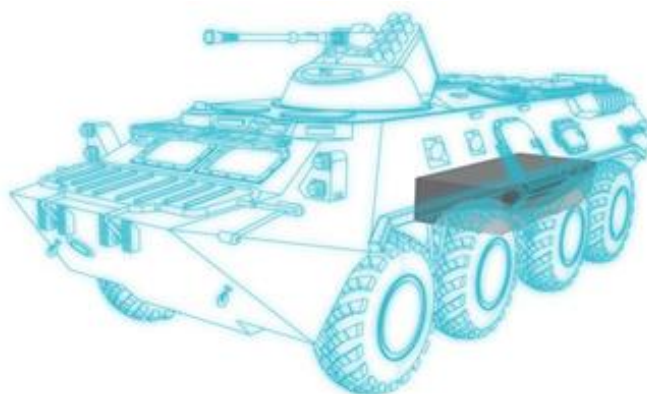


Figure 15 - Military Vehicle Fuel Tank Location

3. Material Selection

3.1 Liner

The liner is a critical component providing the primary barrier to prevent hydrogen leakage. Because of hydrogens small molecular size and high permeability risk, materials like polymers and metals are selected [22].

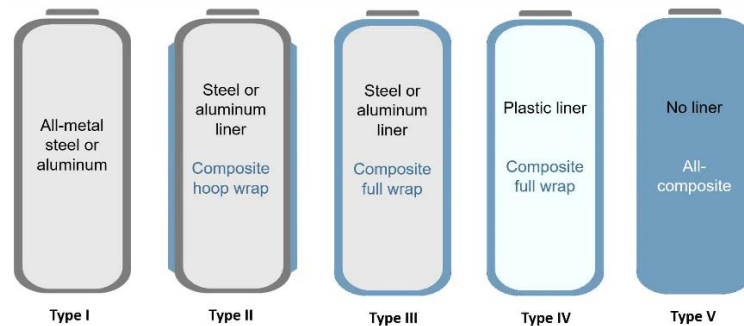


Figure 16 - Types of Hydrogen Vessels

Liner Material	Advantages	Limitations	Applications
Polymer	- Lightweight and flexible. - Low hydrogen permeability. - Chemically resistant to hydrogen & environmental factors. - Cost-effective for large scale production.	- Limited durability under high-pressure - Not suitable for high temperature environments.	Type IV hydrogen tanks
Aluminium Alloy	- Excellent hydrogen impermeability. - Corrosion resistance. - Lightweight compared to other metallics.	- Expensive compared to polymers. - Hydrogen embrittlement under certain conditions.	Type III hydrogen tanks
Stainless Steel	- Extremely durable and resistant to high pressures and temperatures. - Excellent hydrogen impermeability. - Compatible with cryogenic (liquid hydrogen) storage.	- Heavy - Hydrogen embrittlement over time if not properly alloyed. - Expensive for large scale or lightweight applications.	Industrial applications
Titanium	- Exceptional embrittlement & permeation resistance. - Extremely durable & corrosion resistant. - Lightweight compared to steel.	- Very expensive.	High-performance aerospace or specialised applications.

Figure 17 - Liner Material Comparison

The Boxer will utilise an aluminium alloy liner, classifying it as a Type III hydrogen vessel. Type III vessels are commonly used in high-pressure applications due to their

durability and strength. Aluminium liners provide excellent resistance to hydrogen permeation and offer a robust solution for maintaining structural integrity under extreme conditions, making them well-suited for military environments where durability and safety are critical.

3.2 Shell/Reinforcement

The shell reinforces the liner by encasing it in a material, typically CFRP, a composite made of carbon fibres embedded in a polymer matrix. Renowned for its exceptional strength-to-weight ratio, CFRP is ideal for the Boxer, as it withstands high pressures while minimising the overall weight of the hydrogen storage system [23] [24].

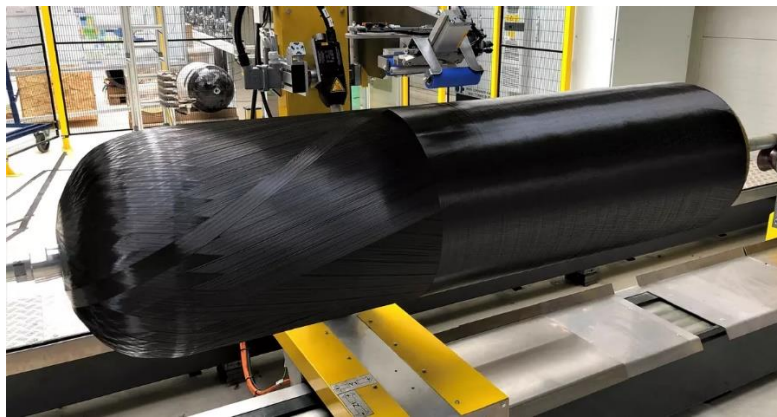


Figure 18 - Carbon4Tan wrapped in CFRP

To enhance the durability of the CFRP shell, a hybrid layer of Kevlar fibre will be added. Known for its with extremely long molecular chains, Kevlar has exceptional tensile strength and resistance to cuts, abrasions, and impacts, providing additional protection against external damage such as shrapnel and debris. While this would slightly increase the vessels weight, it would significantly improve resistance to punctures and ballistic threats, ensuring the hydrogen storage system remains robust and reliable in combat conditions [25].

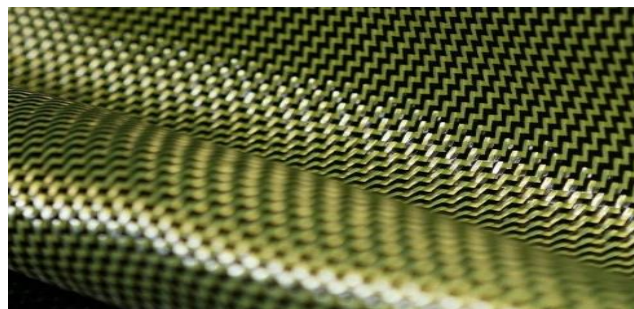


Figure 19 - Kevlar Fibre

3.3 Vehicle

The specific type of steel used in the Boxer's construction is not well-documented, but material selection must account for the effects of hydrogen embrittlement. Martensitic and ferritic steels with Body-Centred Cubic (BCC) crystal structures, commonly used in armoured vehicles, are prone to hydrogen-induced delayed fracture, white spots, and pressure cracking, making them less suitable for hydrogen-powered applications. Austenitic stainless steels with Face-Centred Cubic (FCC) structures, such as 316L Stainless Steel, are more resistant to hydrogen embrittlement and better suited for high-pressure hydrogen systems, though they may still experience ductility loss or cracking under specific conditions. Titanium alloys, while resistant to embrittlement, are vulnerable to hydride formation, which can compromise structural integrity. The Boxer will use low carbon 316L Stainless Steel because of its hydrogen resistance, mechanical strength, and cost-effectiveness. The coating will be electroless nickel plating for its impermeability, corrosion resistance and durability [26].

4. Manufacturing

4.1 Aluminium Alloy

Aluminium alloy liners for hydrogen storage vessels are manufactured using advanced forming techniques such as backward extrusion, a process that is ideal for producing seamless, high-strength components required in high-pressure environments like military vehicles. The process begins with aluminium alloy billets, selected for their excellent mechanical properties, such as resistance to hydrogen embrittlement and high pressure, particularly alloys like AA6061 or AA7000. These billets are heated to above their recrystallisation temperature (300–600°C), enhancing their malleability and enabling the production of near-net shape components. [27].

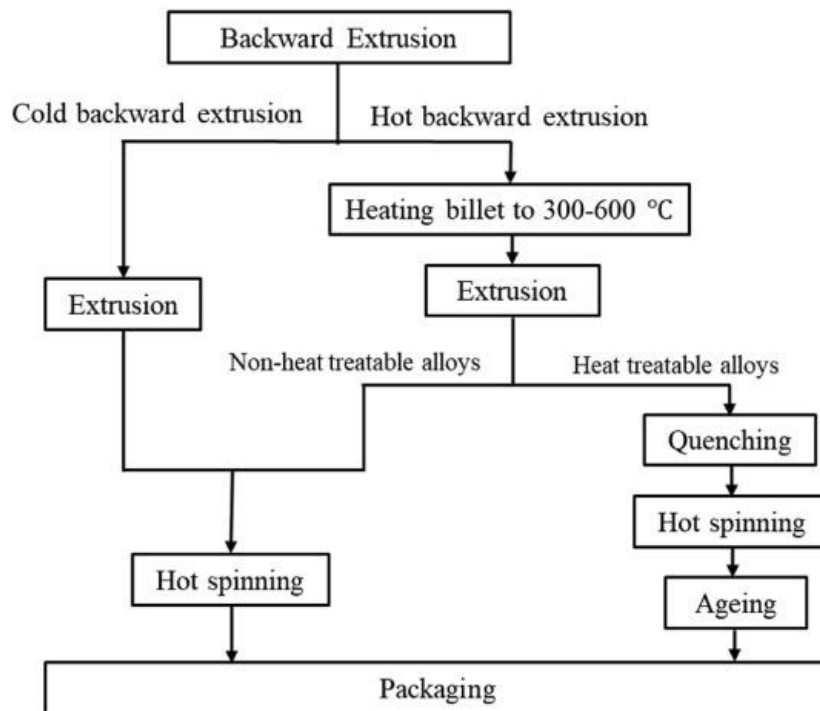


Figure 20 - Flowchart for processing aluminium alloy cylinder

In backward extrusion, the heated billet is pressed using a die and punch system, with material flow directed opposite to the punch movement, forming a cylindrical liner without the need for welding. This method not only ensures excellent structural integrity but also reduces weak points prone to hydrogen leakage. Grain refinement during extrusion, achieved through dynamic recrystallisation, significantly enhances the yield strength of the aluminium alloy by reducing grain size to the sub-micron range. [28].

Post-extrusion, the liner undergoes additional processing to meet stringent hydrogen storage requirements. Trimming and machining refine critical dimensions, such as connection ports, while surface treatments like anodising or chemical coatings enhance corrosion resistance and adhesion to the composite overwrap. Non-Destructive Testing (NDT), including ultrasonic and hydrostatic pressure testing, ensures the liner's integrity under the operational pressures of up to 700 bar. A nitride coating will be applied to prevent diffusion of hydrogen into the alloy [29].

The use of aluminium alloy liners provides several advantages, including exceptional strength, low hydrogen permeability, and resistance to embrittlement. While heavier than the initial idea of using a polyamide liners, aluminium offers the durability and

robustness required for military applications, such as the UK Army Boxer. This method ensures that aluminium liners meet the demanding requirements of hydrogen-powered military vehicles, balancing performance, safety, and operational reliability.

Manufacturing aluminium alloy liners involves risks such as thermal hazards during extrusion and welding, respiratory risks from metal dust and fumes, and exposure to corrosive chemicals during surface treatments. These are mitigated through Protective Personal Equipment (PPE), Local Exhaust Ventilation (LEV), and strict operational controls. NDT ensures liner integrity, while compliance with standards like COSHH (Control of Substances Hazardous to Health) ensures safety and reliability.

4.2 Carbon Fibre Reinforced Plastics

The production of CFRP begins with the creation of carbon fibres, derived from a precursor material such as polyacrylonitrile (PAN). The PAN fibres are stabilised in air at 200–300°C to prepare them for carbonisation. During carbonisation, the fibres are heated to 1,000–2,000°C in an inert environment to remove non-carbon elements, leaving pure carbon fibres. These fibres undergo surface treatment, such as chemical and electrochemical processing, to enhance bonding with the polymer matrix. A protective coating, known as sizing, is then applied to improve handling and integration. The polymer matrix, often an epoxy resin, is prepared for use as the binding agent for the carbon fibres. The fibres are arranged in specific patterns, such as unidirectional or woven layouts, to optimise mechanical properties and strength in desired directions. The fibres are then impregnated with resin using methods like resin transfer moulding or prepreg layup.

The liner is reinforced with Carbon Fibre Reinforced Polymer (CFRP) using filament winding, a process that provides additional strength and bears most of the structural load. Continuous strands of carbon fibre, impregnated with resin, are precisely wound onto the liner in a helical configuration to balance circumferential and axial stresses. The liner is mounted on a winding machine to ensure even coverage and optimal reinforcement.

For enhanced protection in military environments, Kevlar fibre can be added as an additional layer over the CFRP, offering increased resistance to external impacts, such as shrapnel or debris. After the winding process, the vessel undergoes curing in an autoclave or controlled oven at temperatures between 120–180°C, solidifying the resin and creating a strong bond between the fibres and the polymer matrix. This combination of aluminium's inherent strength, CFRP's lightweight resilience, and optional Kevlar protection ensures the Boxer's hydrogen storage system is robust, efficient, and capable of withstanding the extreme conditions of military operations. Post-processing includes trimming excess material and conducting rigorous non-destructive testing, such as ultrasonic scanning and pressure cycling tests, to ensure the structural integrity of the vessel [30].

Manufacturing and handling CFRP for hydrogen storage systems involve risks such as carbon fibre dust exposure, resin handling hazards, and thermal risks during curing. These are mitigated through PPE, local exhaust ventilation, and strict operational controls. Regular NDT ensures the integrity of CFRP components during operation, while fire-retardant coatings enhance safety in extreme conditions. For disposal, recycling through pyrolysis or certified facilities minimises environmental impact. Adherence to standards like COSHH ensures safe manufacturing, operation, and disposal of CFRP components in military applications.

4.3 Kevlar Fibre

Reinforcing the CFRP with Kevlar fibres follows a similar process to the CFRP application. The Kevlar fibre is impregnated with resin to form a composite material, which is then wrapped around the CFRP layer using filament winding, ensuring even coverage and alignment for optimal strength. During the manufacturing process, safety measures aligned with COSHH regulations must be observed. Resin handling requires adequate ventilation, gloves, and eye protection to prevent skin irritation or chemical burns. Fibre dust generated during cutting or sanding must be managed using local exhaust ventilation (LEV) and respiratory protective equipment to avoid inhalation risks. Once applied, the Kevlar layer is cured in an autoclave to solidify the resin and bond it securely to the CFRP. This additional layer significantly improves the vessel's toughness, protecting it from punctures, abrasions, and ballistic impacts, while ensuring manufacturing safety and regulatory compliance.

5. Cost Analysis

Although the upfront costs for hydrogen retrofitting are substantial, the Boxer's enhanced safety, durability, and efficiency justify the investment. The use of CFRP, Kevlar, and high-pressure vessels ensures reliability in combat scenarios, while hydrogen fuel significantly reduces operational emissions, aligning with future military sustainability goals [31].

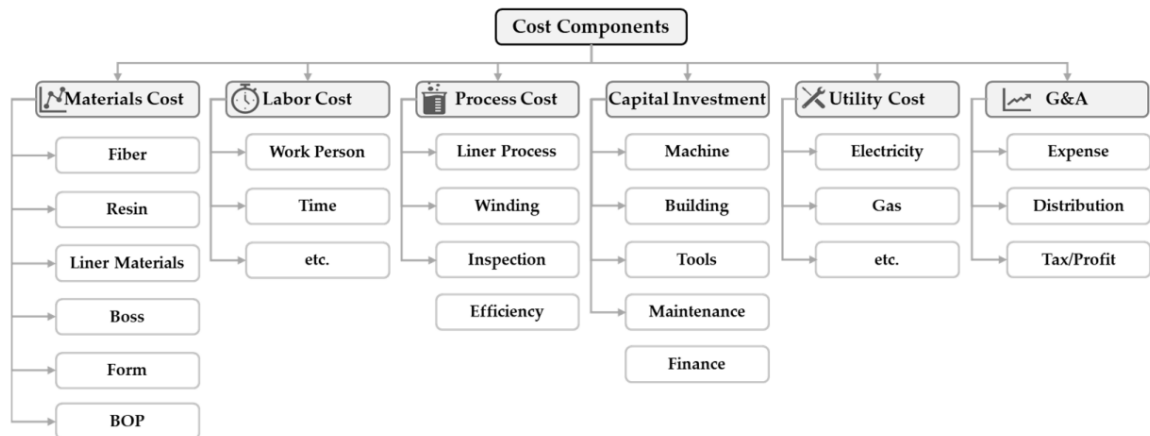


Figure 21 – Component of cost modelling for compressed gas hydrogen storage vessels

Component/Material	Min Cost (GBP) Max	Details	Machine
Billet Preparation	£ 500,000.00 £ 1,500,000.00	Ensuring high-quality surfaces	SNK MS-24
Liner Cylinder Extrusion	£ 10,000.00 £ 50,000.00	Producing seamless high-pressure liners.	Schuler Deep Drawing Press
Liner Dome Moulding	£ 5,000.00 £ 20,000.00	Moulding polyamide liners for durability.	Beckwood Triform
Liner Planning & Joining	£ 5,000.00 £ 25,000.00	Ensures leak-free connections.	ESAB LEGIO Friction Stir
Surface Treatment	£ 150,000.00 £ 500,000.00	Toughens surface of material.	Plasma (Ion) Nitriding
Fibre Winding (CFRP)	£ 150,000.00 £ 500,000.00	Reinforces liner for high-pressure use.	Roth
B-Stage Curing	£ 15,000.00 £ 64,000.00	Intermediate curing for resin application (autoclave)	Sapphire 770E VAC DE
Full Cure (Pressurised)	£ 15,000.00 £ 64,000.00	Solidifies resin for structural strength (autoclave)	Sapphire 770E VAC DE
Tank Shoulder Foam Application	£ 15,000.00 £ 20,000.00	Provides structural stability and insulation (robotic)	Spraybot Ultra
Kevlar Layer Application	£ 150,000.00 £ 500,000.00	Reinforces liner for high-pressure use.	Roth
Leak Testing	£ 16,000.00 £ 16,000.00	Ensures tank integrity (helium leak detector)	INFICON UL1000 Fab
Hydrostatic Testing	£ 50,000.00 £ 150,000.00	Tests pressure of vessel.	SCITEQ SIGMA
Visual Inspection	£ 120.00 £ 200.00	Boxer requires 8 hours. Average Hourly Rate (£15-£25)	N/A
	£ 1,081,120.00 £ 3,409,200.00		

Table 1 - Machine Process Costs

Material Costs		
Component/Material	Cost (GBP)	Details
CFRP	30–40/kg	Lightweight, high-strength composite.
Kevlar Fibre	40–60/kg	High tensile strength for impact resistance.
Aluminium	3–4/kg	Cost-effective liner material.

Table 2 - Material Cost

Hydrogen Fuel Costs		
Component/Material	Cost (GBP)	Details
Hydrogen (Cost per kg)	10–15	Cost per kg of hydrogen.
Total Hydrogen Cost (500 miles)	564–845	Estimated cost for 500-mile range.

Table 3 - Hydrogen Fuel Costs

Hydrogen System Costs		
Component/Material	Cost (GBP)	Details
Hydrogen Engine (H2-ICE)	250000	Robust, field-maintainable engine.
Fuel Cell System	350,000–400,000	Higher efficiency, lower operational emissions.

Table 4 - Hydrogen System Cost

The prices in the analysis reflect the cost of purchasing state-of-the-art equipment brand new with a minimum cost of £1,081,000 and a maximum of £3,409,00. These costs would be higher when factoring in labour, bills and infrastructure. However, these costs would decrease significantly when spread across the total number of units produced. With over 500 Boxers manufactured, if 200 hydrogen-powered units are ordered, the per-unit cost of the equipment would be considerably reduced [32].

6. Conclusion

This report has assessed the feasibility of retrofitting the Boxer armoured vehicle with hydrogen power from a material science perspective, focusing on materials and manufacturing techniques required for high-pressure hydrogen storage systems. Key considerations included selecting materials that balance strength, durability, and hydrogen resistance to meet the demands of military environments while maintaining operational reliability.

The use of aluminium alloy liners for hydrogen containment, classifying the Boxer as a Type III hydrogen vessel, was identified as a robust solution. Aluminium provides excellent resistance to hydrogen permeation and embrittlement while maintaining the structural integrity necessary for high-pressure environments. Manufacturing processes such as extrusion and friction stir welding ensure seamless and durable liner construction. For reinforcement, Carbon Fibre Reinforced Polymer (CFRP) was selected for its outstanding strength-to-weight ratio and ability to withstand high pressures, with optional Kevlar fibre layers enhancing impact and abrasion resistance for combat scenarios.

The cost analysis revealed that while the upfront expenses for materials and state-of-the-art manufacturing equipment are substantial, spreading these costs over a fleet of hydrogen-powered Boxers significantly reduces the per-unit investment. For instance, advanced processes like fibre winding and curing contribute to the reliability of the system but add to the overall cost. However, the long-term benefits, such as improved safety, reduced emissions, and alignment with sustainability goals, justify the investment.

In conclusion, the successful integration of hydrogen systems into the Boxer depends on advanced material science and precise manufacturing. The adoption of aluminium alloy liners, reinforced with CFRP and Kevlar, ensures the system's durability and safety while addressing the unique challenges of military operations. Continued research into material innovations and cost-efficient manufacturing will further enhance the feasibility and operational performance of hydrogen-powered military vehicles.

There were various design options for the vehicle's hydrogen storage system. In an ideal scenario where cost, weight, and space were not constraints, a spherical pressure vessel would be optimal, theoretically withstanding 1.5 times the pressure by evenly distributing stress across its surface, eliminating weak points. While Granta EduPack would have been an excellent tool for material selection and analysis, access was unfortunately limited.

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2 Appendix

Polyamide – original liner

Polyamide liners for hydrogen storage vessels are commonly manufactured using rotational moulding (rotomoulding), a process well-suited for creating seamless, durable, and lightweight components. The process begins with polyamide resin, often enhanced with glass fibres or other additives to improve strength and durability, being loaded into a mould. The mould is then heated to temperatures exceeding the polyamide's melting point (e.g. 223°C for PA6) to ensure complete melting and adhesion of the polymer to the mould walls. Simultaneously, the mould is rotated along multiple axes, allowing the molten resin to evenly coat the inner surface and form a uniform, seamless layer. After cooling to solidify the material, the liner is carefully removed from the mould.

Factor	Aluminium (Type III)	Polyamide (Type IV)
Weight	Heavier	Lightweight
Cost	More expensive	More cost-effective
Pressure Resistance	Excellent	Good, but less robust
Hydrogen Permeation	Very low	Low
Durability	High	Moderate
Temperature Range	Wide	Limited

Once the liner is formed, it undergoes post-processing to ensure precision and performance. Trimming and machining remove any excess material and achieve precise dimensions, particularly at connection points or valve ports. Surface treatments, such as plasma treatment or chemical etching, are applied to enhance the liner's surface energy, ensuring strong adhesion between the liner and the composite shell during subsequent bonding. The liner is then subjected to rigorous non-destructive testing, including ultrasonic testing to detect internal defects and hydrostatic pressure testing to verify its integrity under high-pressure conditions. Rotomoulding provides

several advantages, including uniform wall thickness, lightweight and the structural integrity necessary for high-pressure hydrogen storage. This method ensures that polyamide liners meet the stringent demands of applications such as hydrogen-powered vehicles, offering a balance of durability, precision, and cost-effectiveness.



Ineos Gladiator

