MECH 4860

Hydrogen Fuel Cell System Layout Design

Motor Coach Industries

UNIVERSITY OF MANITOBA

TEAM 1

FIRST CHOICE CONSULTANTS

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EXECUTIVE SUMMARY

Motor Coach Industries is seeking to expand their propulsion system offerings to include hydrogen fuels cells built within the J4500e electric coach chassis. The objective of the team is to design a hydrogen fuel cell layout that is compatible with the J4500e electric coach, whilst minimizing space claim and maximizing range of operation. This report outlines the final layout design for the hydrogen fuel cell system, which includes the fuel cell stacks, battery pack, and hydrogen storage tanks as the major components. Other project deliverables such as a Piping and Instrumentation Diagram, costs of major components, and a Failure Modes and Effects Analysis are also presented in this report.

Customer needs were identified to guide the team towards the optimal solution. The most important project needs were to maximize coach range and minimize hydrogen leakage while adhering to all applicable vehicle standards. Engineering metrics were established based on these needs and were used as evaluation criteria for the final design.

For the overall system, hydrogen fuel cell stacks and the amount of batteries were determined [redacted] and [redacted] Using this information, [redacted] were selected that maximized coach range and adhered to the coach's internal volume constraints. Using these major components, several layout concepts were screened and scored, and the optimal concept was further developed into the final design.

The final design was developed by designing the intake and exhaust of the fuel cell stacks, as well by determining the hydrogen piping between all appropriate components. The intake and exhaust were designed considering the required pressure drop and space claim impacts. The hydrogen piping was designed to minimize fittings required, and by assuring emergency hydrogen venting measures were considered. The final design has [redacted] and 1 XALT XMP76P battery pack. These specifications give a theoretical hydrogen fuel cell coach a range of 7 hours at a constant speed of 60 mph. The overall cost of the hydrogen fuel cell system is [redacted]

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1. INTRODUCTION

Motor Coach Industries is a subsidiary of New Flyer Industries based in Winnipeg, Manitoba. Motor Coach Industries define themselves as "... North America's leading manufacturer of intercity coaches serving charter and tour operators; line-haul and scheduled-service operators; transit agencies; and conversion companies in the U.S. and Canada" [1]. Motor Coach Industries' current product lines consist of coaches with multiple methods of propulsion including diesel, compressed natural gas and hybrid diesel electric. An all-electric coach is currently in the testing phase, with the company looking to expand further through the inclusion of hydrogen fuel cell technology [1]. Both the electric coach and the hydrogen fuel cell coach would be offered under the J4500e line chassis, with the hopes of both coaches sharing common components and a general layout.

Although electric systems are commonly available, the introduction of hydrogen fuel cell technology is an innovative and novel approach. Hydrogen fuel cell systems are comprised of hydrogen storage tanks, fill panels, fuel cell stacks, battery packs, battery management systems (BMS), battery thermal management systems (BTMS) and fuel cell thermal management systems (FCTMS). The configuration of such a system is shown in Figure 1.

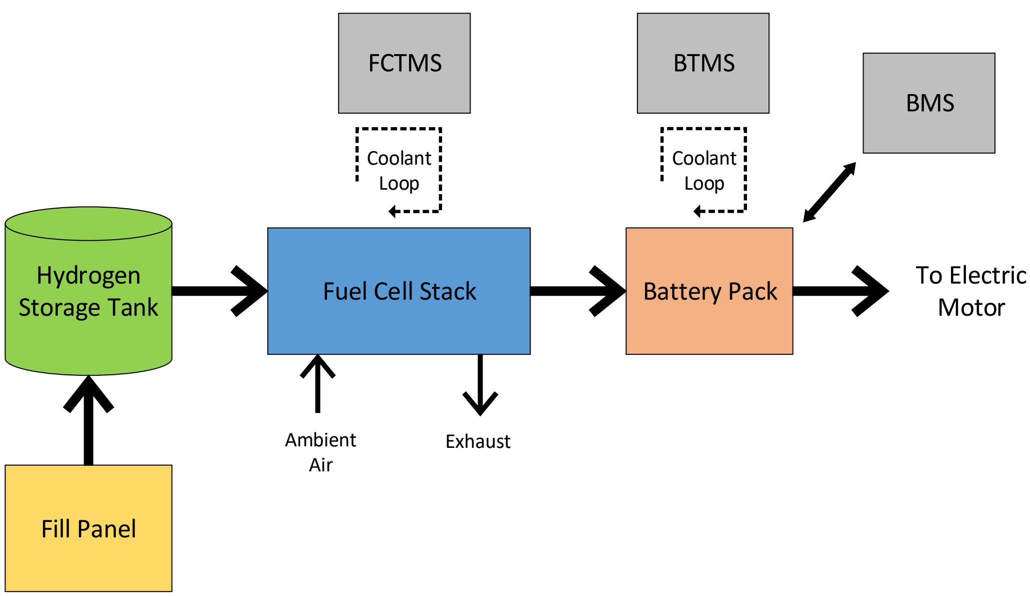


Figure 1. Hydrogen fuel cell system diagram

As shown in Figure 1, the hydrogen storage tanks supply the needed fuel through the fill panel to the fuel cell stack. The ambient air in conjunction with the supplied hydrogen generate power within the fuel cell stack that is used to charge the battery pack, which in turn drives the electric motor. The BMS, the BTMS and the FCTMS operate in tandem to monitor battery pack operating conditions and eliminate the heat produced from the fuel cell stack and the battery pack, respectively.

The power generating component within the hydrogen fuel cell system is the fuel cell stack. The stack is composed of multiple hydrogen fuel cells in a series configuration, working together to produce the needed output power [2]. Hydrogen from the storage tank is routed to the cell stack along with ambient air. Oxygen from the air reacts at the cathode, while hydrogen reacts at the anode. The electrons liberated from the decomposition of the gases at the electrodes pass through a polymer electrolyte membrane which produces an electrical current that is used to charge the batteries [2]. Figure 2 showcases an example of a fuel cell stack system from [redacted]

[redacted]

Many of the components within the hydrogen fuel cell system required for complete vehicle functionality are shared with its electric system counterpart. The current setup of Motor Coach Industries' J4500e electric coach is shown in Figure 3.

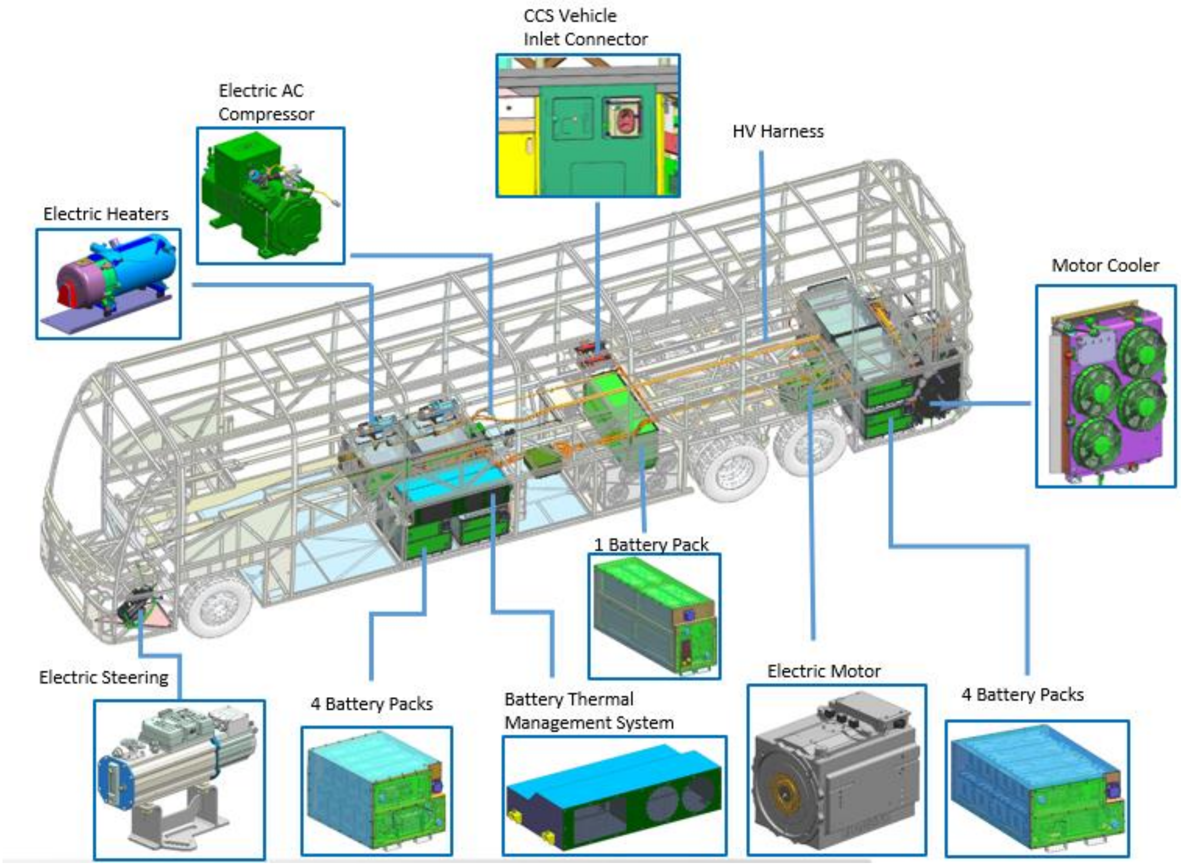


Figure 3. CAD render of current electric coach propulsion system [4]

Given Motor Coach Industries' J4500e electric coach, the challenge is to integrate a hydrogen fuel cell system within the current electric coach design. This novel approach requires the restructuring of current electric components, the sourcing and integration of hydrogen storage tanks, fill panels, fuel cell stacks and necessary line routing, along with the proper layout of battery packs, BMS, BTMS, FCTMS and electric heaters. The hydrogen fuel cell system layout must act cohesive within the J4500e coach, meeting all of Motor Coach Industries' standards.

1.1 Objectives

The purpose of this project is to integrate the layout of a hydrogen fuel cell system within Motor Coach Industries' J4500e electric coach. The hydrogen fuel cell system is comprised of the fuel cell stacks, the battery packs, the hydrogen storage tanks, the fill panel, the BMS, the BTMS, the FCTMS and all necessary line routing required to integrate the hydrogen fuel cell system to the electric housing.

The hydrogen fuel cell system must be integrated in a manner which minimizes change to the existing structure of the coach and minimizes its space claim within the coach frame. Furthermore, the hydrogen fuel cell system must adhere to all applicable hydrogen fuel cell automotive standards. Safety is of paramount importance, thus, appropriate design choices must be made to ensure the safety of personnel and property. Table I lists the deliverables, as requested by Motor Coach Industries, at the completion of this project.

TABLE I: LIST OF PROJECT DELIVERABLES

#	**Deliverable**
1	CAD model of layout
2	Piping & Instrumentation Diagram (P&ID)
3	Vendor list and cost of major components
4	Failure modes and effects analysis (FMEA)

The testing and verification of each component in the hydrogen fuel cell system, along with a complete thermal analysis and any electrical assembly is considered out of scope for this project. Additionally, the team is to assume that each component within the hydrogen fuel cell system will function as intended.

To attain all required deliverables, the analysis of this project is divided into two phases. The first phase consists of a concept development process, focusing on the major components within the hydrogen fuel cell system, including the selection of the fuel cell stack, the battery pack and the hydrogen storage tank, as well as their layout within the J4500e coach. The BMS, the BTMS, the FCTMS and the electric heater are also considered. The second phase consists of a detailed design analysis, focusing on the layout of all auxiliary components within the hydrogen fuel cell system, including the fill panel and all necessary line routing required to integrate the hydrogen fuel cell system to the electric housing. This report contains a summary of the first phase and focuses on the analysis of the second phase within the hydrogen fuel cell system layout design project.

1.2 Customer Needs

The development of customer needs aid in the establishment of design considerations for the hydrogen fuel cell system. In collaboration with Motor Coach Industries, along with stakeholders New Flyer Industries and Ballard Power Systems, 13 needs were developed. Each need is given a value of importance on a scale of one to five, with one being least important and five being most important. The overall project needs are shown in Table II.

TABLE II: CUSTOMER NEEDS

#	Need	Importance
1	The hydrogen fuel cell system follows all applicable standards and adheres to all applicable regulations.	5
2	The hydrogen fuel cell system cannot leak into the cabin.	5
3	The hydrogen fuel cell system maximizes range of the coach.	5
4	The hydrogen fuel cell system components are easy to access for maintenance.	4
5	The hydrogen fuel cell system is easily integrated into the current coach layout.	4
6	The hydrogen fuel cell system has appropriate weight distribution.	3
7	The hydrogen fuel cell system maximizes baggage space.	3
8	The hydrogen fuel cell system is easy to install.	3
9	The hydrogen fuel cell system is cost-effective.	3

Detailed information regarding the customer needs are in Appendix A.

1.3 Constraints and Limitations

To create a feasible and viable hydrogen fuel cell system, constraints were set in terms of the scope of this project. Table III shows the list of constraints and limitations applicable to this project.

TABLE III: CONSTRAINTS AND LIMITATIONS

#	Constraint	Description
1	Cost Effective Design	The hydrogen fuel cell system must be cost effective in comparison to other propulsion methods within Motor Coach Industries' product lines.
2	Timeline of Project	All project deliverables must be completed by December 5th, 2018.
3	J4500e Coach Availability	All components within the hydrogen fuel cell system must fit within the coach.
4	Battery Pack Requirements	All battery packs employed in the analysis of this project are those provided by XALT Energy.
5	Fuel Cell Requirements	[redacted]
6	Hydrogen Storage Tank Selection	All tanks employed in the analysis of this project are those provided by Hexagon Composites, in conjunction with New Flyer Industries.
7	Total Power Requirements	The average total power required is [redacted]
8	Compatibility	The hydrogen fuel cell system must be compatible with the J4500e coach, with all components seamlessly integrating into the existing coach.
9	Maintenance and Accessibility of Fuel Cell Stack	The hydrogen fuel cell stack must be accessible to persons on the interior and exterior of the coach for maintenance purposes.
10	Range of Operation	The hydrogen fuel cell system must be functional within both city and highway driving conditions, given a maximum operation time of ten hours and a temperature range of -40°C to 40°C.
11	Standards	The hydrogen fuel cell system must adhere to all applicable hydrogen vehicle standards.

Detailed information regarding the constraints and limitations are in Appendix B. Additionally, Table IV shows the list of standards relevant to the design of the hydrogen fuel cell system.

TABLE IV: LIST OF STANDARDS

Ref.	**Standard**
A	ANSI HGV2 Compressed Hydrogen Gas Powered Vehicle Fuel Containers
B	ANSI/CSA HGV3.1 Fuel System Components for Hydrogen Gas Powered Vehicles
C	ANSI/CSA HPRD 1 Thermally Activated Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers
D	ASME B31.12 Hydrogen Piping and Pipelines
E	CGA G-5.5 Hydrogen Vent Systems
F	CSA B109 Natural Gas for Vehicles Installation Code
G	EC79/2009 Vehicles Council on Type-Approval of Hydrogen-Powered Motor Vehicles
H	EC79/EU 406 Vehicles Council on Type-Approval of Hydrogen-Powered Motor Vehicles
I	NFPA-2 Hydrogen Technologies Code
J	NFPA-52 Vehicular Natural Gas Fuel Systems Code
K	SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety
L	SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
M	SAE J2601-2 Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles

Table V relates each standard to the individual components within the hydrogen fuel cell system.

TABLE V: COMPONENT SPECIFIC STANDARDS

	Standard												
Component	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
Fuel Storage System						**X**	**X**			**X**	**X**	**X**	
Hydrogen Storage Tanks	**X**							**X**				**X**	
Tank Valves		**X**						**X**					
Thermal Pressure Relief Devices			**X**		**X**			**X**					
Fuel Handling System (Fuel Lines)				**X**		**X**		**X**	**X**	**X**		**X**	
Fill Receptacle													**X**
Air Intake, Exhaust, Cooling System											**X**		

Adhering to all constraints and limitations is crucial to ensure a feasible and viable solution for the hydrogen fuel cell system.

1.4 Engineering Metrics

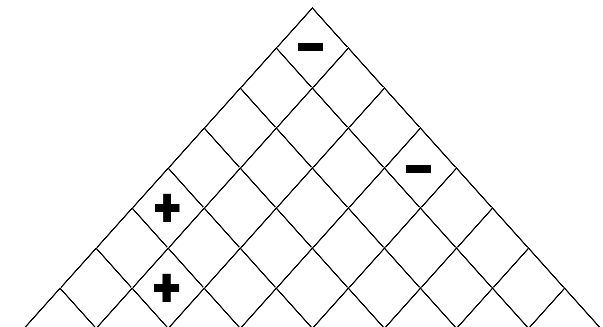
Engineering metrics were determined to evaluate the achievement of all customer needs. Each metric is given an importance value on a scale of one to five which corresponds with the need it addresses, in addition to a marginal value and an ideal value. Some metrics are quantitative and are evaluated by a value with a unit of measurement, some metrics are subjective and are evaluated by a panel of five selected stakeholders from Motor Coach Industries' and some metrics are binary and are either achieved or not achieved. The list of metrics are shown in Table VI.

TABLE VI: ENGINEERING METRICS

#	Metric	Imp.	Units	Marginal Value	Ideal Value	Needs Addressed
1	Ease of accessibility of hydrogen fuel cell components.	4	subj.	-	Board Approval	4, 8
2	All applicable standards met.	5	binary	-	Yes	1, 2
3	The selected design adequately prevents hydrogen leakage from entering the cabin.	5	subj.	-	Board Approval	2
4	The selected design is easily integrated into the current coach layout.	4	subj.	-	Board Approval	5
5	The range that the hydrogen fuel cell coach can achieve at a constant speed of 96.6 km/h.	5	hours	>8	>10	3
6	Number of baggage bays available.	3	int.	>0	>1	7
7	Reasonable considerations are given to keep hydrogen fuel cell system costs low.	3	subj.	-	Board Approval	9
8	The weight distribution of the hydrogen fuel cell system is adequately similar to that of the battery-electric system.	3	subj.	-	Board Approval	6

Detailed information regarding the metrics are in Appendix D. A House of Quality showing customer needs, engineering metrics, relative importance values, marginal and ideal values, as well as relationships between needs and metrics are shown in Figure 4.

Interactions:
+ Positive
− Negative



#	Customer Needs	Imp.	1	2	3	4	5	6	7	8
	Engineering Metrics		Ease of accessibility of hydrogen fuel cell components	All applicable standards met	The selected design adequately prevents hydrogen leakage from entering the cabin	The selected design is easily integrated into the existing current coach layout	The range that the hydrogen fuel cell coach can achieveat a constant speed of 96.6 km/h	Number of baggage bays available	Reasonable considerations are given to keep hydrogen fuel cell system costs low	The weight distribution of the hydrogen fuel cell system is adequately similar to that of the battery-electric system
		Imp.	4	5	5	4	5	3	3	3
1	The hydrogen fuel cell system follows all applicable standards and adheres to all applicable regulations.	5		•						
2	The hydrogen fuel cell system cannot leak into the cabin.	5		•	•					
3	The hydrogen fuel cell system maximizes range of the coach.	5					•			
4	The hydrogen fuel cell system components are easy to access for maintenance.	4	•							
5	The hydrogen fuel cell system is easily integrated into the current coach layout.	4				•				
6	The hydrogen fuel cell system has appropriate weight distribution.	3								•
7	The hydrogen fuel cell system maximizes baggage space.	3						•		
8	The hydrogen fuel cell system is easy to install.	3	•							
9	The hydrogen fuel cell system is cost-effective.	3							•	
	Measurement Units		subj.	bin.	subj.	subj.	hours	int.	subj.	subj.
	Marginal Value		-	-	-	-	>8	>0	-	-
	Ideal Value		B.A.	Yes	B.A.	B.A.	>10	>1	B.A.	B.A.

Figure 4. House of Quality

2. PRODUCT SPECIFICATIONS

This section explores all available product lines for the fuel cell stacks, the battery packs, the hydrogen storage tanks, as well as all necessary line routing components which fall within the project scope and adhere to project constraints.

2.1 Fuel Cell Stacks

There are three fuel cell stacks employed in the analysis of this project; the [redacted] the HD85 and the HD100 models, all of which are provided by Ballard Power Systems. Table VII summarizes the product specifications of the listed fuel cell stacks.

TABLE VII: FUEL CELL STACK SPECIFICATIONS [5]

Specifications	[redacted]	**HD85**	**HD100**
Power Capacity (kW)	[redacted]	[redacted]	[redacted]
Mass (kg)	[redacted]	[redacted]	[redacted]
Dimensions (l × w × h, mm)	[redacted]	[redacted]	[redacted]
Compliance to Standards	[redacted]		

All listed specifications are utilized to determine the ideal fuel cell stack for this project. Further details regarding all fuel cell stack specifications are in Appendix E.

2.2 Battery Packs

The battery pack employed in the analysis of this project is the XMP76P high density lithium-ion battery packs, provided by XALT Energy in conjunction with Motor Coach Industries. The packs are composed of seven modules, in parallel configuration. Table VIII summarizes the product specifications of the XMP76P battery modules.

TABLE VIII: XMP76P BATTERY MODULE SPECIFICATIONS [6]

Specifications	**Module**
Energy (kWh)	7.6
Mass (kg)	76.8
Dimensions (l × w × h, mm)	753 x 303 x 282
Cost (USD)	[redacted]
Compliance to Standards	ISO 12405, ISO 16750, UNT R100, GMW 16390, UNDOT 38.3, IEC 62281, J2929

Further details regarding the XMP76P battery pack specifications are in Appendix F.

2.3 Hydrogen Storage Tanks

There are 13 hydrogen storage tanks employed in the analysis of this project, ranging from Model A to [redacted], listed in alphabetical order. All hydrogen storage tanks are provided by Hexagon Composites, in conjunction with New Flyer Industries, and [redacted] standards. Table IX summarizes the product specifications of the listed hydrogen storage tanks.

TABLE IX: HYDROGEN STORAGE TANK SPECIFICATIONS [7]

Tank Model	**Nominal Working Pressure (bar)**	**Mass (kg)**	**Hydrogen Capacity (kg)**	**Outside Diameter (mm)**	**Length (mm)**
A	200	16	0.7	315	1060
B	250	164	8.0	541	2783
C	250	94	6.0	503	2342
D	300	112	7.2	509	2342
E	350	101	7.5	420	3190
F	350	112	8.4	509	2342
G	500	280	16.5	565	3277
H	500	229	10.7	531	2424
I	700	34	1.4	319	906
J	700	29	1.6	238	1600
K	700	43	2.6	420	845
L	700	59	3.1	440	1050
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

All listed specifications are utilized to determine the ideal hydrogen storage tanks for this project. Further details regarding the hydrogen storage tank specifications are in Appendix G. [redacted]

2.4 Hydrogen Line Routing

The hydrogen fuel cell system includes hydrogen line routing which is comprised of tubing and components that operate simultaneously to route hydrogen fuel between the fuel cell stacks and the hydrogen storage tanks. The specifications for all tubing and components are detailed in the following sections.

2.4.1 Tubing

Tubing is required to transfer the hydrogen fuel throughout the hydrogen fuel cell system. [redacted] is used in the design of the hydrogen fuel cell system. Specifications for the selected tubing are shown in Table X.

TABLE X: SWAGELOK TUBING SPECIFICATIONS [8]

Specification	**Swagelok FK Series Tubing**
Material	[redacted]
Outer Diameter (in.)	[redacted]
Wall Thickness (in.)	[redacted]
Weight (kg/m)	[redacted]
ASME B31.3 Pressure Rating (bar)	[redacted]
Recommended Bend Radius (mm)	[redacted]

Further details regarding the selected hydrogen tubing are in Appendix H.

2.4.2 Components

There are various components employed in the hydrogen line routing, for low-pressure and high-pressure applications, within the hydrogen fuel cell system. Table XI summarizes the required components, along with their suppliers and working pressure. [redacted]

TABLE XI: HYDROGEN COMPONENT SPECIFICATIONS

Fitting	**Supplier**	**Product Identifier**	**Working Pressure**
Check Valve	[redacted]	[redacted]	[redacted]
Fill Receptacle	[redacted]	[redacted]	[redacted]
Hand Shut-off Plug Valve	[redacted]	[redacted]	[redacted]
Hand Shut-off Plug Valve	[redacted]	[redacted]	[redacted]
Needle Valve	[redacted]	[redacted]	[redacted]
Particle Filter	[redacted]	[redacted]	[redacted]
Port Quick Connect	[redacted]	[redacted]	[redacted]
Port Quick Connect	[redacted]	[redacted]	[redacted]
Pressure Gauge	[redacted]	[redacted]	[redacted]
Pressure Gauge	[redacted]	[redacted]	[redacted]
Pressure Regulator	[redacted]	[redacted]	[redacted]
Pressure Relief Valve	[redacted]	[redacted]	[redacted]
Pressure Transducer	[redacted]	[redacted]	[redacted]
Solenoid Valve	[redacted]	[redacted]	[redacted]

Further details regarding the selected hydrogen line routing components are in Appendix I.

3. CONCEPT DEVELOPMENT SUMMARY

This section contains a summary of the concept development phase within the hydrogen fuel cell system layout project, beginning with the derivation of the J4500e coach power requirements as this parameter is the foundation of all subsequent analysis.

To determine the coach power requirements, duty cycles were first established. As the J4500e coach must operate in both city and highway conditions, two duty cycles were developed: one simulating city conditions and one simulating highway conditions. In addition, the duration of operation was limited to ten hours as this is the maximum period a coach may be operated continuously. Further descriptions of the duty cycles are in Appendix J.

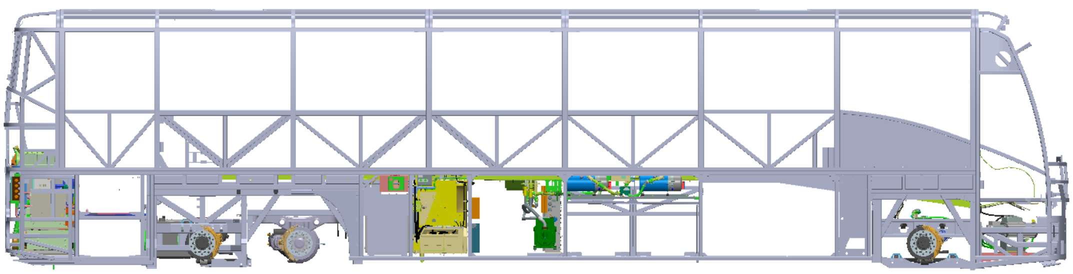
Having identified the required duty cycles, the J4500e coach power requirements were established for city conditions and highway conditions. This power analysis was conducted theoretically with a tractive effort study and experimentally through test data. The average J4500e coach power draw was calculated to be [redacted], reflective of the experimental analysis for highway conditions. All detailed calculations are in Appendix J.

With the calculated power draw, a screening and scoring process was performed for the fuel cell stacks through the evaluation of specified selection criteria. The selection criteria included power capacity, number of batteries required, mass, envelope and ease of maintenance. The selected system included [redacted] fuel cell stacks. The detailed screening and scoring processes, along with all relevant calculations are in Appendix K and Appendix L.

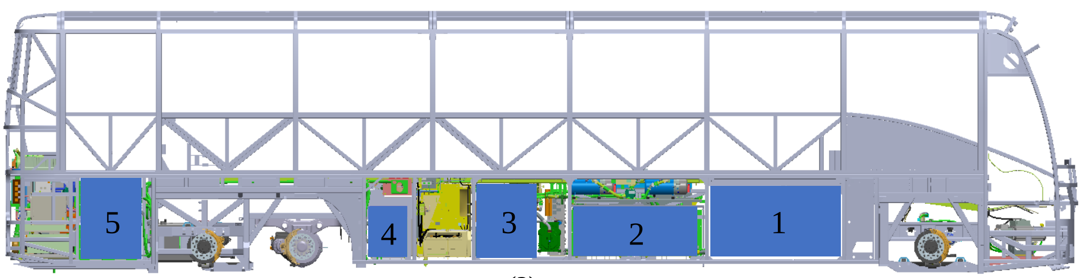
Once the fuel cell stacks were selected, the efficiency of the system was maximized by balancing the capacity of the batteries with the capacity of the hydrogen fuel, while adhering to all space restrictions within the J4500e coach. Iterative calculations were performed with the fuel cell stacks operating at a lower net output power, giving an optimized battery capacity of one pack with [redacted] kg of hydrogen fuel. All detailed efficiency calculations are in Appendix M.

Using the calculated hydrogen fuel capacity, along with four specified selection criteria, including pressure rating, number of tanks required, mass, and envelope, a screening and scoring process was performed for the hydrogen storage tanks. The selected system included [redacted] which met the required hydrogen fuel capacity. The detailed screening and scoring processes, along with all relevant calculations are in Appendix N and Appendix O.

With all major components selected and optimized, the hydrogen fuel cell stacks, the battery packs, and the hydrogen storage tanks were configured into varying layouts along with the BMS, the BTMS, the FCTMS and the electric heater. The design space is divided as shown in Figure 5.



(1)



(2)

Figure 5. J4500e compartment division

As shown in Figure 5, (1) displays the compartments within the J4500e coach, while (2) dictates a compartment number to each area. Using this numbering format, four layouts were analyzed with a final screening and scoring process. The specified selection criteria included J4500e coach re-design, safety, relative center of gravity and complexity.

The selected fuel cell system layout is shown in Figure 6, Figure 7 and Figure 8. The detailed screening and scoring processes, along with all relevant calculations are in Appendix P and Appendix Q.

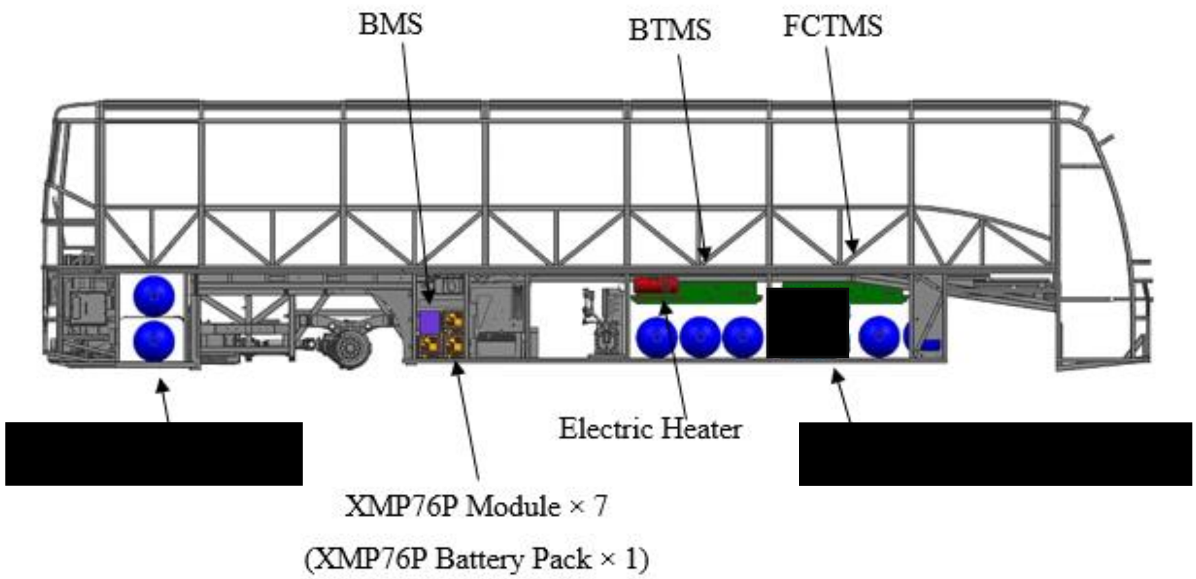


Figure 6. Selected fuel cell system layout passenger side view

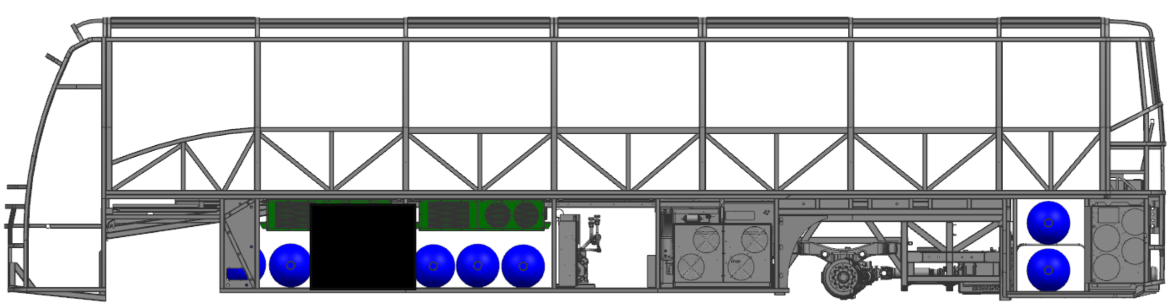


Figure 7. Selected fuel cell system layout driver side view

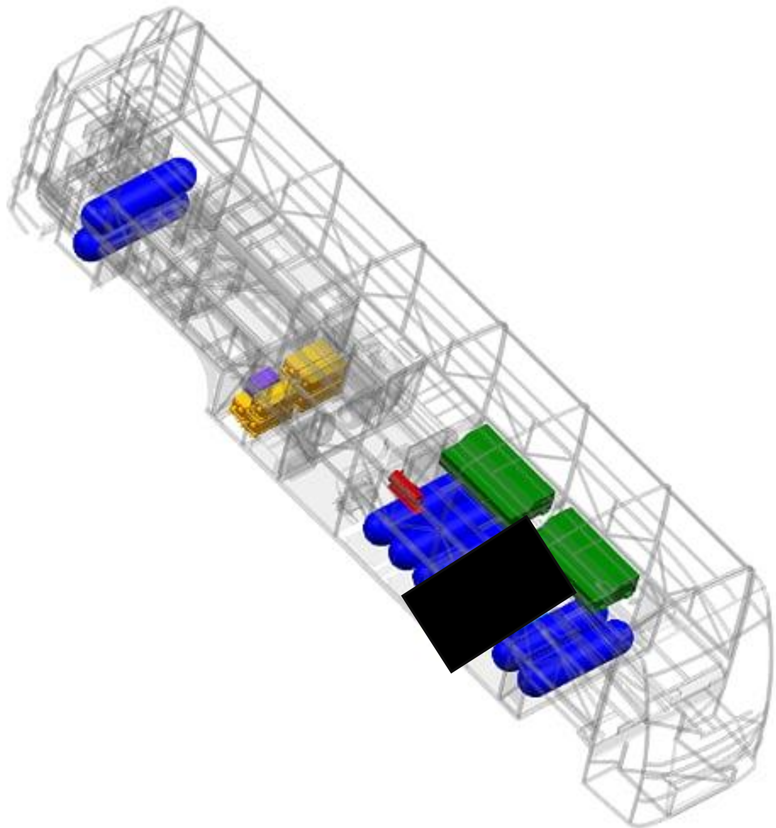


Figure 8. Selected fuel cell system layout isometric view

With the selection of an optimal fuel cell system layout containing all major components as well as the BMS, the BTMS, the FCTMS and the electric heater, phase one was completed. All subsequent analysis pertains to phase two of this project.

4. FINAL DESIGN

This section provides a detailed overview of the final fuel cell system layout design. The detailed design includes specifications for the core components, the intake and exhaust, as well as the hydrogen line routing system. Project objectives including the CAD models of the final design, the vendor list and costs, and the FMEA is also presented. A discussion of how the final design compares to the established metrics of the project concludes this section.

4.1 Major Components

The major components of the hydrogen fuel cell system were selected and placed within the frame of the coach in the concept development phase, and consist of the fuel cell stack, the hydrogen storage tanks and the battery pack.

[redacted] were chosen as the power plant for the hydrogen fuel cell system. [redacted]

[redacted] The fuel cell stacks each require air piping, hydrogen lines and coolant lines to be routed to their inlet ports. The fuel cell stacks also require exhaust piping and coolant lines to be routed from their outlet ports. The air intake and exhaust piping designs are detailed in Section 4.2 and the hydrogen line routing design is detailed in Section 4.3.

The battery pack for the hydrogen fuel cell system consists of seven XMP76P battery modules from XALT Energy, along with a battery management system. The battery pack modulates the power from the fuel cell stacks to drive the coach's electric motors. The total energy capacity of the battery pack is 53.2 kWh, used to make up the difference between the power consumed by the coach and the power produced by the fuel cell stacks.

[redacted] hydrogen storage tanks from Hexagon Composites were selected for the hydrogen fuel cell system. [redacted]

[redacted] The hydrogen storage tanks store a total of [redacted] of hydrogen fuel at 700 bar aboard the coach. Hydrogen lines are routed from the hydrogen storage tanks to the fill panel and fuel cell stacks.

4.2 Air Intake and Exhaust

The air intake piping supplies air to the fuel cell stacks, which is pumped through the system using their respective air compressors.

The intake piping was designed to meet pressure drop requirements and minimize space claim. The material for the intake piping was selected to be ABS plastic, since this is a common and low-cost intake material. [redacted]. The intake piping for each fuel cell run from their respective chemical filters and join with a y-connector. The particle filter was placed upstream of the exhaust outlet to avoid humid and oxygen deficient air from the exhaust. The particle filter was also placed as high as possible in the compartment to avoid any dust thrown by the front tire. The intake piping design is shown in Figure 9 and Figure 10.

Ballard Power Systems specifies a maximum air intake pressure drop value that the air intake can impose at the maximum expected air flow rate. Since the [redacted] fuel cell module is still under development and the value for maximum air intake pressure drop has not yet been determined, the value for the HD85 fuel cell module is used as an approximation. In the integration manual for the HD85, a maximum air intake pressure drop of [redacted] is specified at a maximum air flow rate of [redacted]. Ballard also indicates that further reduction in intake pressure drop improves the net power output of the fuel cell by reducing the power consumption of the compressor.

The expected pressure drop in the intake system was determined through pressure loss calculations deriving from Bernoulli's equation and using the Darcy friction factor. The expected pressure drop for each fuel cell stack was found to be [redacted]. Pressure drop calculations for the intake piping are in Appendix R.

The exhaust piping removes the products of the hydrogen fuel cell reaction, being water and air at a temperature of 50°C to 75°C.

Like the intake design, the exhaust piping was designed to meet pressure drop requirements and minimize space claim. The material for the exhaust piping was selected to be stainless steel piping for its strength and corrosion resistant properties. A four-inch diameter was used throughout the exhaust runs to maintain the same diameter as the exhaust connection of the fuel cell stacks. Each fuel cell stack has its respective exhaust pipe to simplify the manufacturing process and follow a path of minimized resistance to the lower corner of the compartment. The exhaust piping design is shown in Figure 9 and Figure 10.

Ballard Power Systems specifies a maximum exhaust backpressure value that the exhaust can impose. Since the [redacted] fuel cell module is still under development and the value for maximum exhaust backpressure has not yet been determined, the value for the HD85 fuel cell module is used as an approximation. In the integration manual for the HD85 [20], a maximum exhaust backpressure of [redacted] is specified at a maximum air flow rate of [redacted]

Similar to the intake pressure drop, expected backpressure in the exhaust system was determined through pressure loss calculations deriving from Bernoulli's equation and using the Darcy friction factor. The expected backpressure for each fuel cell stack was found to be [redacted]. Backpressure calculations for the exhaust piping are in Appendix R.

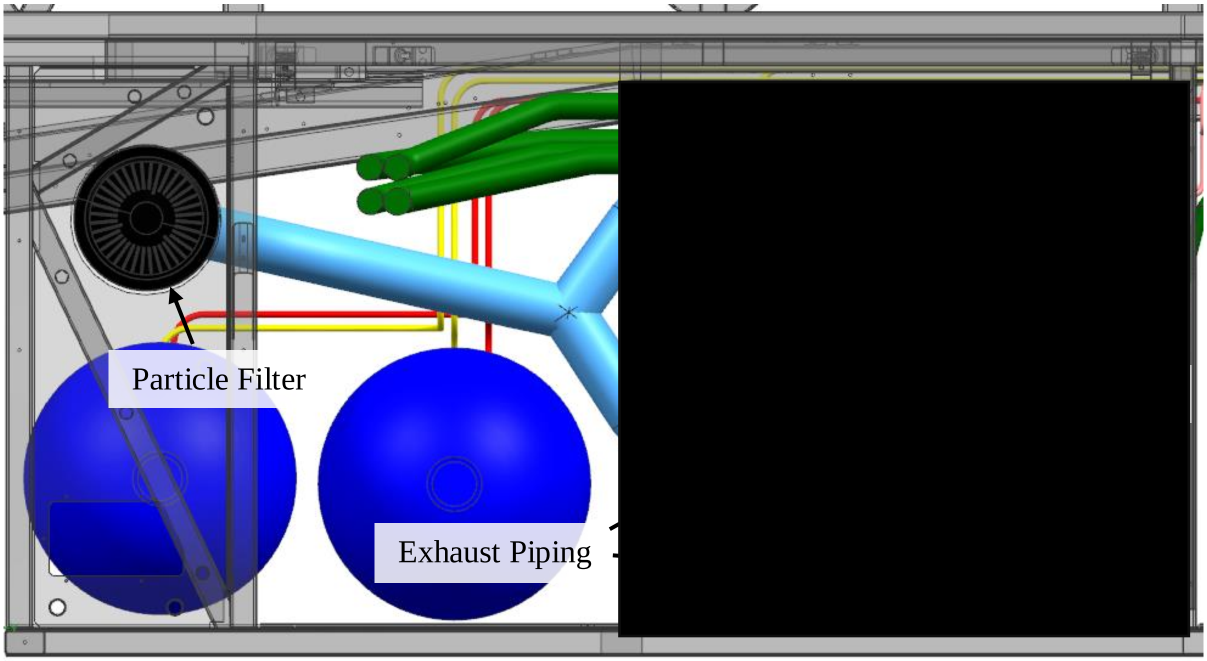


Figure 9. Intake and exhaust design side view

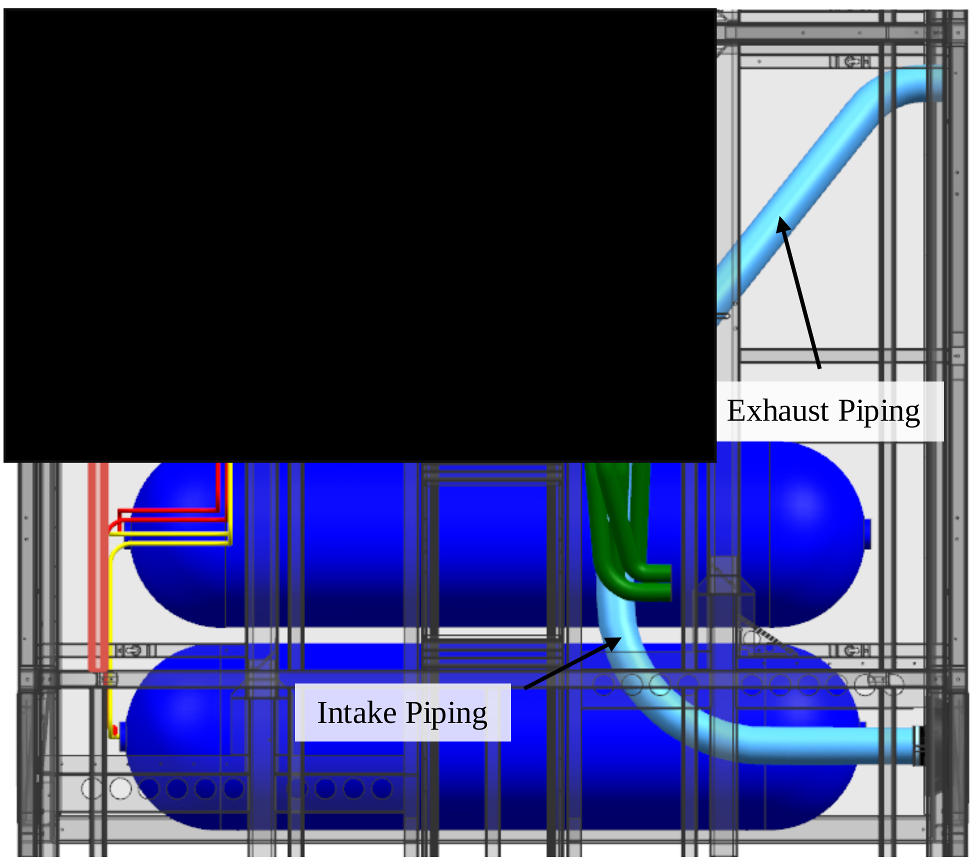


Figure 10. Intake and exhaust design top view

4.3 Hydrogen Line Routing System

The hydrogen line routing system supplies the fuel cell stacks with the appropriate amount of hydrogen fuel from the hydrogen storage tanks and contains various safety measures, such as emergency venting and pressure monitoring. The line routing system consists [redacted], dictated by the pressure rating of the hydrogen storage tanks and a low-pressure side at [redacted] dictated by the hydrogen supply pressure of the fuel cell stacks [21]. Tubing is used for hydrogen flow through the system, while multiple gas handling fittings are used to control and monitor hydrogen fuel properties.

The tubing for the system is selected to withstand the maximum fill pressure of the hydrogen storage tanks [redacted] and minimize pressure loss as hydrogen flows through the system [21]. Swagelok's FK Series medium-pressure tubing was selected for the hydrogen fuel cell system with a working pressure of [redacted] [8]. The same tubing was selected for both the high-pressure and low-pressure sides to protect the system in case of pressure regulator failure. The largest possible outer diameter of 0.75 inches was chosen to minimize pressure losses within the hydrogen fuel cell system. The material was chosen as cold-drawn 1/8-hard 316 stainless steel to minimize wall thickness, as this increases flow area and minimizes pressure losses. Specifications for the selected tubing are shown in Table X and more details are in Appendix H.

4.3.1 Piping and Instrumentation Diagram

The hydrogen lines are routed to adhere to the space availability within the J4500e coach. The overall system is routed to minimize the amount of fittings and bends, which in turn reduces the total pressure loss and the total length of tubing required. The hydrogen line routing system is shown in the P&ID in Figure 11.

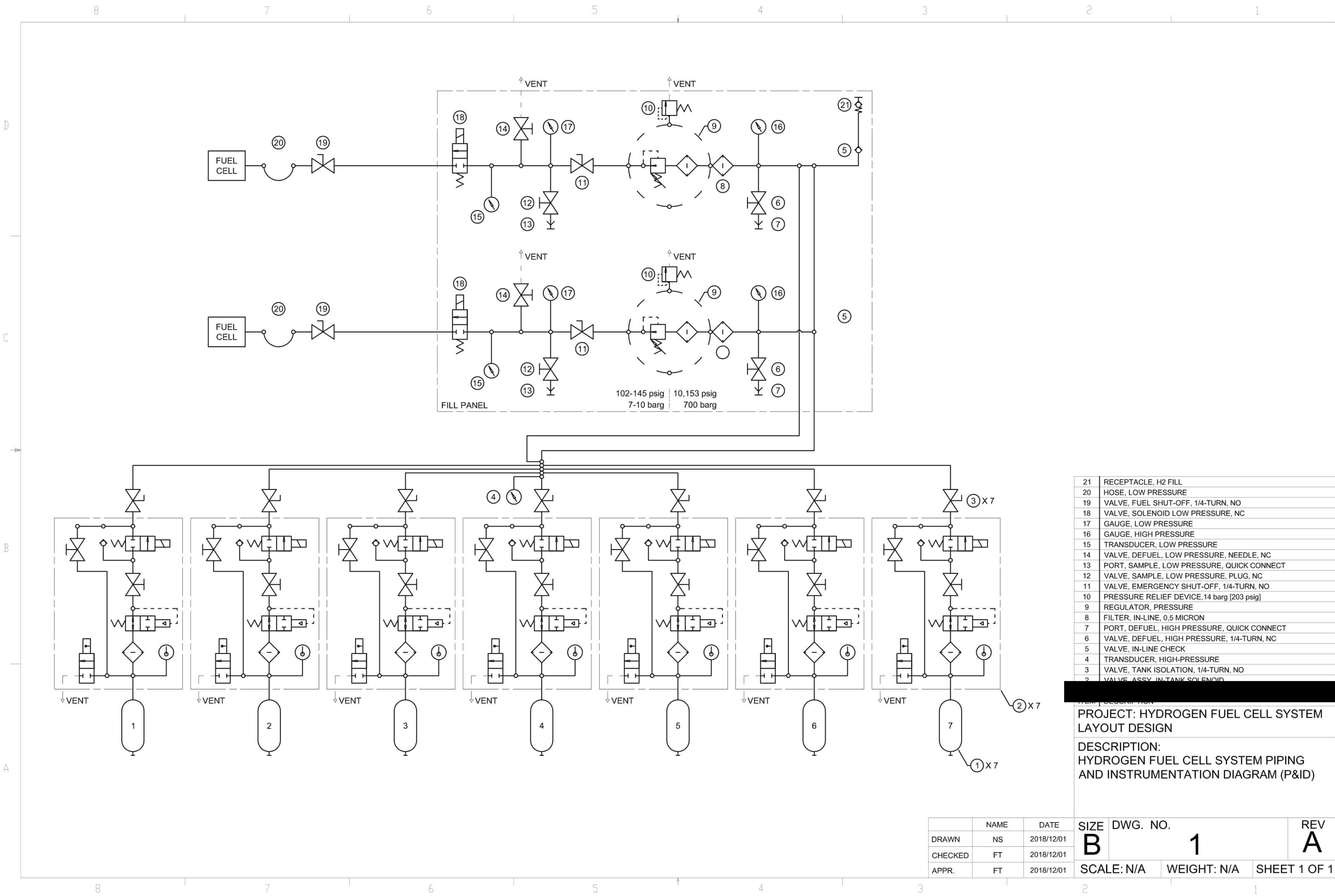


Figure 11. Piping and Instrumentation Diagram

As shown in Figure 11, the high-pressure side consists of the seven hydrogen storage tanks, noted as item one on the P&ID, that store the hydrogen fuel aboard the coach at an operating pressure of 700 bar. The [redacted], item two, is provided by Hexagon Composites in conjunction with [redacted], the original equipment manufacturer. The valve assembly contains a thermal pressure relief valve which operates in conjunction with a thermistor to monitor the temperature of the hydrogen storage tanks. In the case that the temperature of the tanks fall below -40°C or rise above 85°C, the thermal pressure relief will purge the hydrogen fuel from the system to the back of the coach, adding a safety precaution to address potentially dangerous temperatures. Furthermore, the [redacted] allows for connection of the tanks to the rest of the tubing system.

The hydrogen lines are routed from each valve assembly and meet at the center manifold, shown on the P&ID as the junction where the seven hydrogen lines from the hydrogen storage tanks combine. A pressure transducer, item four, is mounted to the manifold to monitor the pressure of the hydrogen storage system. The manifold combines the seven hydrogen lines into two that connect the storage system to the fill panel and fuel cell stacks.

The fill panel combines all of the line routing system’s major components and fittings for ease of maintenance and to limit the areas where the risk of hydrogen leakage is most prominent. The fill panel contains a quick-connect defuel port, item seven, to empty the system of hydrogen if needed. High-pressure gauges are mounted to the fill panel to monitor line pressures of the hydrogen fuel while filling. These are noted as items 16 and 17 on the P&ID. Past the defueling port is the pressure regulator, item nine, which reduces the pressure of the system from 700 bar to [redacted]. The pressure regulator contains a pressure relief device, item 10, to purge the hydrogen fuel from the system to the roof of the coach, adding a safety precaution to address potential pressure regulator failures.

Past the pressure regulator is the low-pressure side, consisting of a manual shut-off valve that cuts off hydrogen fuel supply to the fuel cell stacks for maintenance purposes or in case of an emergency. It is noted by item 11 on the P&ID. Downstream of the manual shut-off valve is the sampling port, item 13, which is used in order to obtain small samples of hydrogen fuel. Furthermore, a low-pressure gauge, item 17, is utilized to monitor the low-pressure line. A defuel valve, item 14, is incorporated to purge the hydrogen fuel from the system to the back of the coach, adding a safety precaution to address potential failures on the low-pressure side. The hydrogen lines continue through a solenoid valve, item 18, operated only when the coach is powered and controlled remotely to dictate flow of hydrogen into the fuel cell stacks.

The fill receptacle, item 21, exists in between the fuel cell stack routes and the hydrogen storage tank routes to refuel the system.

4.3.2 Pressure Analysis

A pressure analysis is conducted on the hydrogen line routing system to determine total pressure loss, both on the low-pressure and high-pressure sides.

The low-pressure side analysis includes a mass flow rate of [redacted] of hydrogen fuel, as dictated by the fuel cell stack specifications [20]. With the given mass flow rate, the major pressure losses are 2416.26 Pa and the minor pressures loss are 763.03 Pa, totalling in low side pressure losses of 3179.29 Pa.

The high-pressure side analysis does not include a restricted mass flow rate, as a fill station vendor could not be established within the time restrictions of this project. Therefore, two reasonable mass flow rates are assumed, 50 g/s and [redacted] and two separate analysis are conducted to attain a feasible range of pressure losses. [redacted] The assumed flow rate is lower due to the pressure differential achievable by fill station suppliers. The fill stations are able to achieve a higher pressure differential for New Flyer Industries' [redacted] than the 700 bar system used in this project. As a result, the achievable flow rate will be higher for New Flyer's system that in this project. The 50 kg/s flow rate is assumed to be a reasonable lower bound value for the fill station suppliers to achieve. Table XII lists the results of the pressure loss analysis, which considers the major and minor losses of the high pressure side system.

TABLE XII: HIGH SIDE PRESSURE LOSSES

Mass Flow Rate (g/s)	**High Side Major Losses (Pa)**	**High Side Minor Losses (Pa)**	**High Side Total Losses (Pa)**
50	1565.93	251.19	1817.12
75	3435.34	551.07	3986.41

Thus, the fill station sourced from a fill station vendor in the future must be able to comply with total pressure losses ranging from 1817.12 Pa to 3986.41 Pa, given a reasonable mass flow rate between 50 g/s to [redacted] respectively. All detailed calculations, including assumptions and input parameters are in Appendix S.

4.4 Final Specifications and CAD Models

This section outlines the final specifications of the hydrogen fuel cell system and provides various views of the final design. Additional considerations in the final design are also discussed in this section. The specifications of the final design are summarized in Table XIII.

TABLE XIII: FINAL SPECIFICATIONS

Parameter	Value
Fuel Cell Stack	[redacted]
Battery Pack	1 × XMP76P (7 Modules)
Hydrogen Storage Tanks	7 × Model M
Range	7 hours @ 96.6 km/h
Hydrogen Capacity	[redacted]
Mass Relative to Electric Coach	[redacted]

A labeled isometric view of the final design isolated from the J4500e coach is shown in Figure 12. All the components within the figures of this section are color coded for ease of interpretation. This color code is shown in Table XIV.

TABLE XIV: COLOUR CODE FOR FINAL DESIGN

Color	**Component**
Grey	J4500e Coach Frame
Light Blue	[redacted] Fuel Cell Stacks
Orange	XMP76P Battery Pack
Navy Blue	Model M Tank
Green	BTMS and FCTMS
Purple	BMS
Red	Electric Heater
Yellow	Fill Panel

The various tubing in the hydrogen fuel cell system is also color coded and is shown in Table XV.

TABLE XV: COLOUR CODE FOR HYDROGEN TUBING

Color	**Medium**	**Tubing**
Yellow	Hydrogen	Fill panel to fuel cell stacks and hydrogen storage tanks
Red	Hydrogen	Safety vents
Green	Coolant	FCTMS and BTMS coolant tubing

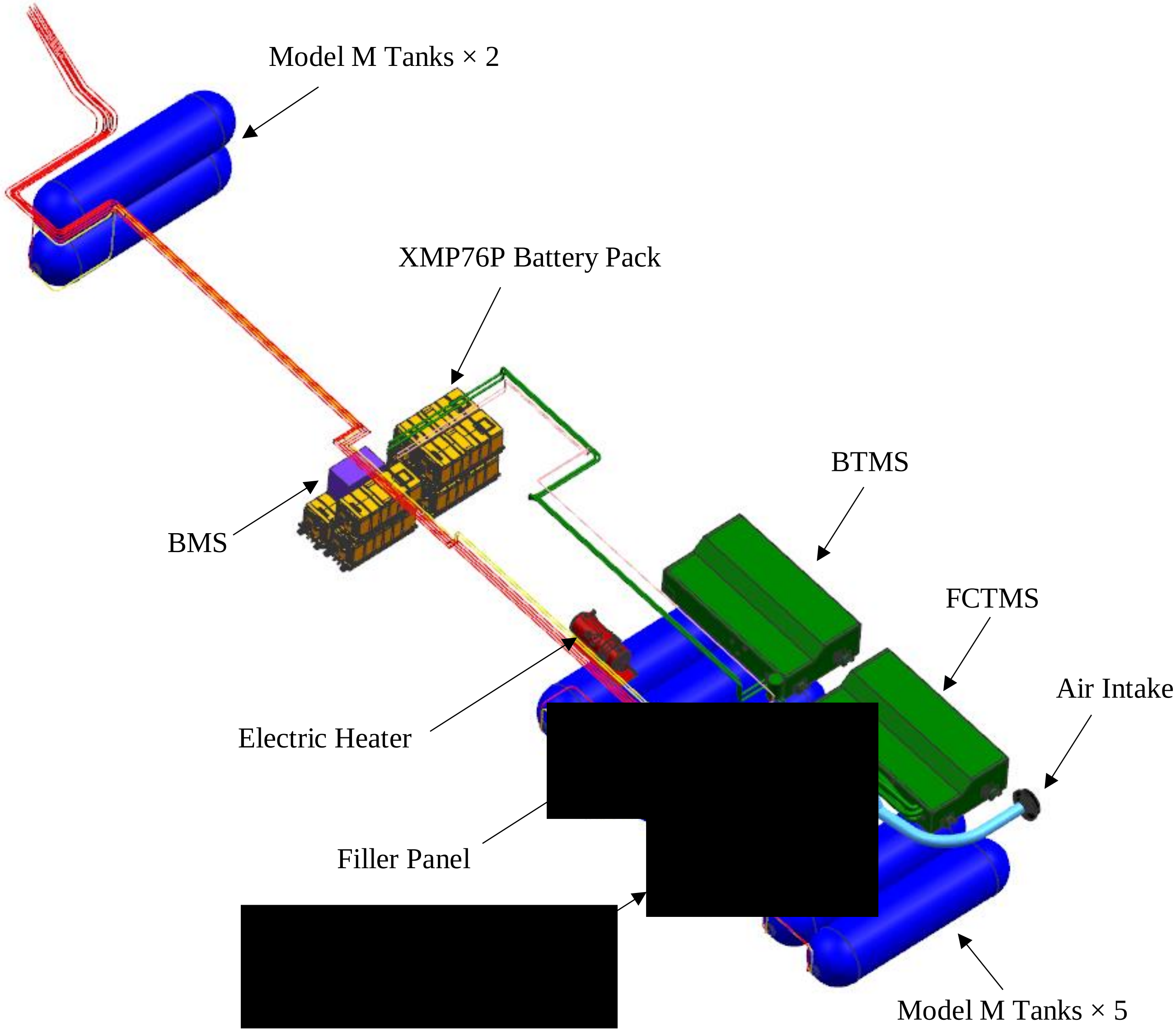


Figure 12. Isometric view of the final layout design in isolation

Figure 13 shows an isometric view of the final layout design in the frame of the J4500e coach.

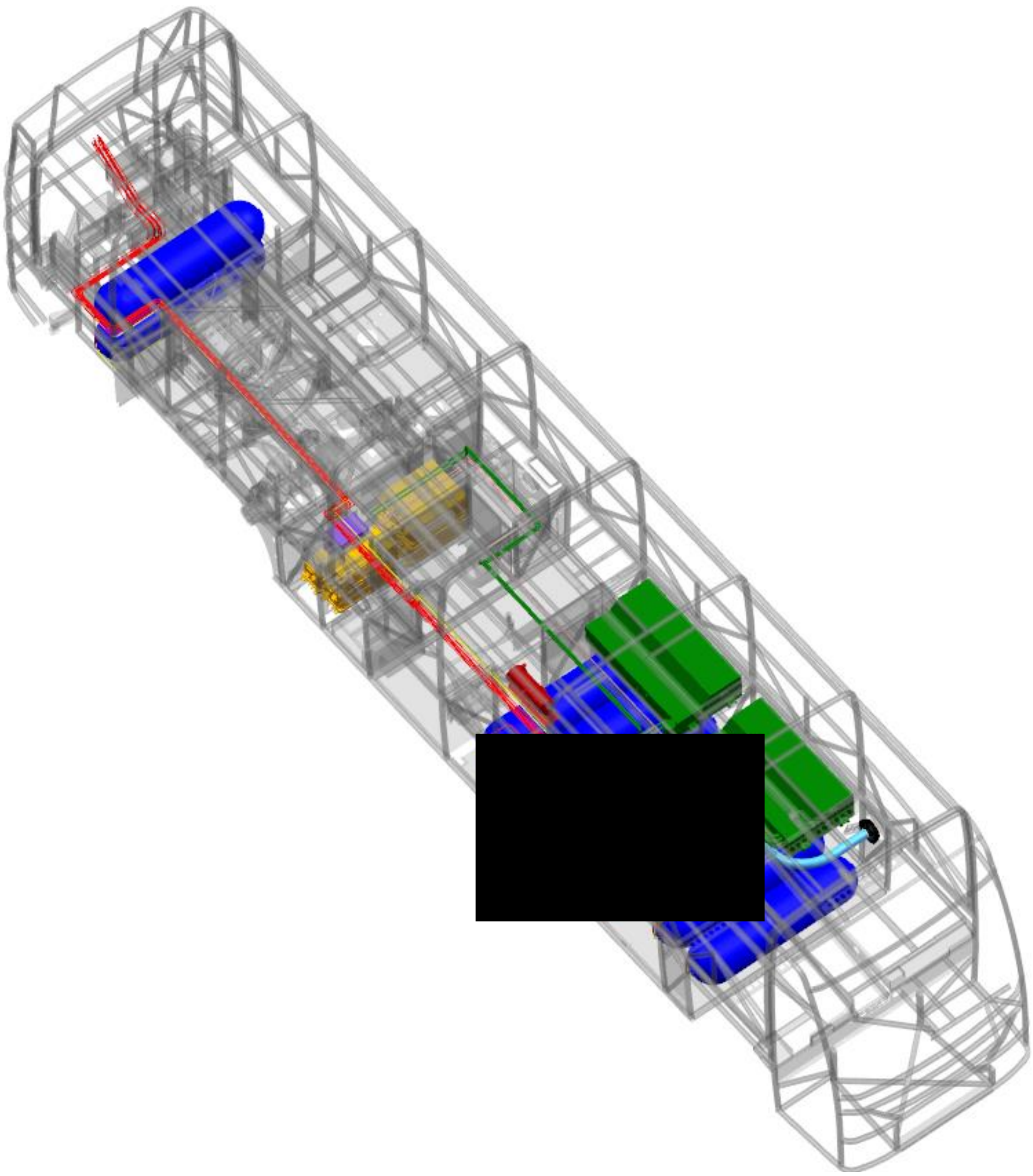


Figure 13. Isometric view of final layout design in the frame of the J4500e coach

Figure 14 and Figure 15 shows detailed views of the final design layout from the road side and the curb side respectively. Figure 16 and Figure 17 show a top and bottom view of the coach respectively, with the front of the coach facing right.

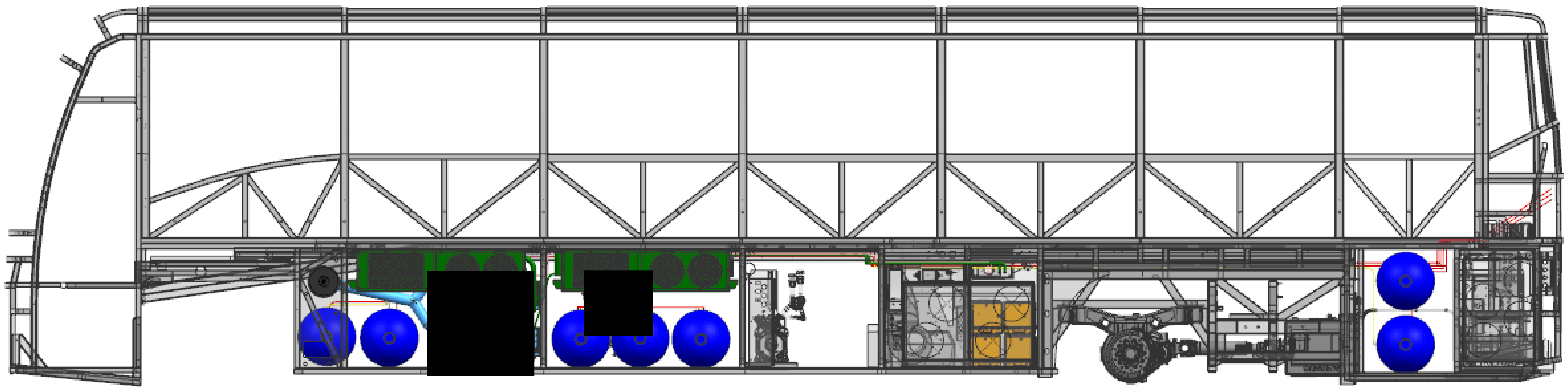


Figure 14. Road side view of the final design layout

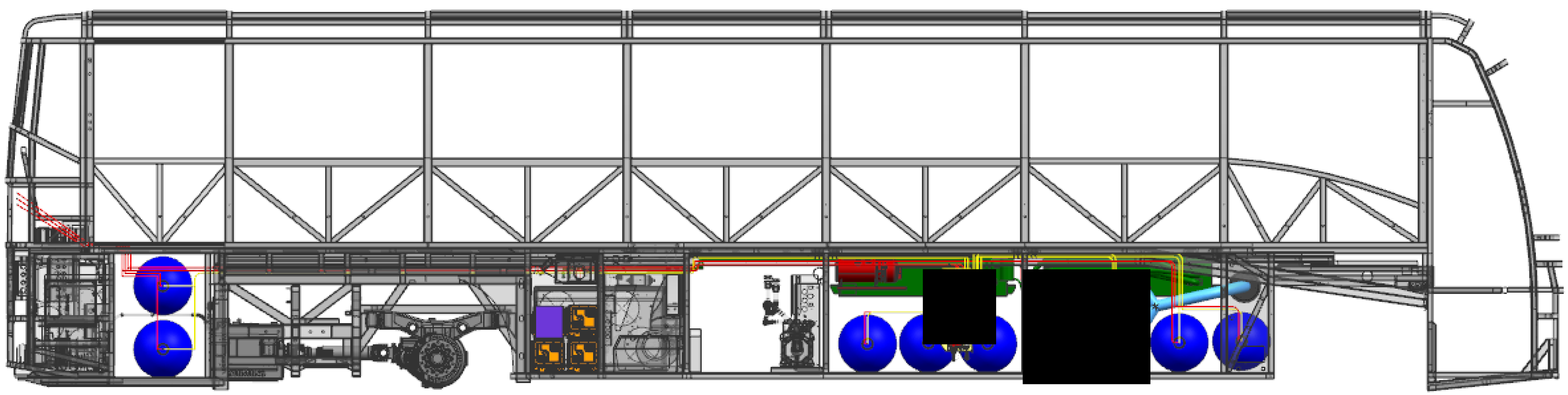


Figure 15. Curb side view of the final design layout

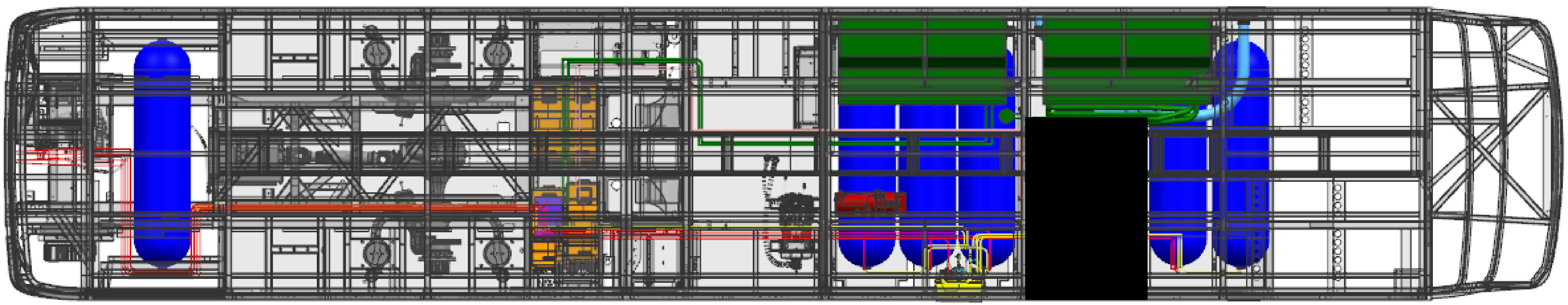


Figure 16. Top view of the final design layout

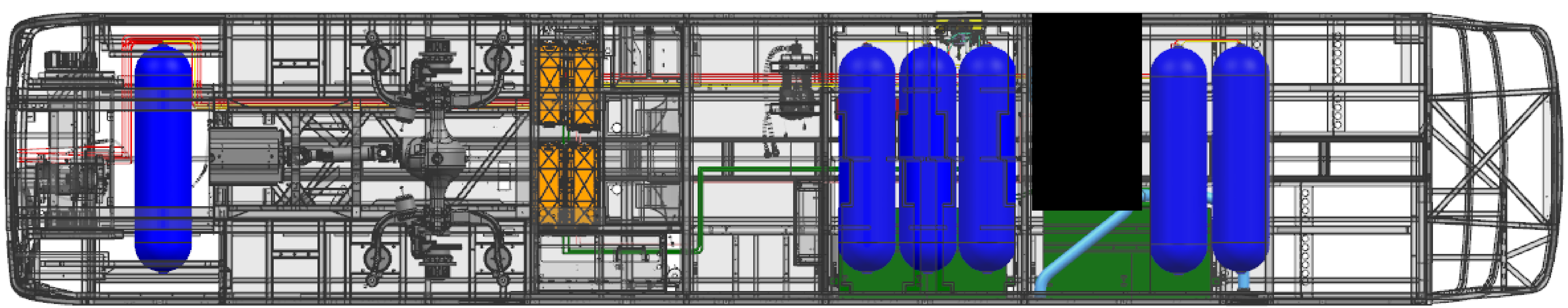


Figure 17. Bottom view of the final design layout

Further considerations in the final design not shown in the above figures are the inclusion of safety vents on the hydrogen fuel cell system access doors, and foam hydrogen sealing of each compartment. Hydrogen gas will collect on the roof of the compartments and will enter the passenger bay if appropriate safety measures are not installed. One of these safety measures is the modification of the fuel cell system access doors to include venting or louvres. The venting allows for the leaked hydrogen gas to disperse and exit the coach to the atmosphere. Furthermore, sealing of each compartment prevents this hydrogen gas from reaching the passenger compartment, and the hydrogen is forced to exit through safety venting. Additionally, sleeves will be placed on hydrogen fittings and joints to further prohibit hydrogen leakage. Hence, these two additional measures work in tandem to improve overall safety of the hydrogen fuel cell system.

4.5 Vendor List and Total Project Budget

This section contains the list of vendors, in conjunction with the costs of major components associated with the hydrogen fuel cell system, as shown in Table XVI.

TABLE XVI: VENDOR LIST AND COST OF MAJOR COMPONENTS

Component	**Model**	**Vendor**	**Cost (USD)**
Fuel Cell Stack	[redacted]	Ballard Power Systems	[redacted]
Battery Pack	XMP76P	XALT Energy	[redacted]
Hydrogen Storage Tank	Model M	Hexagon Composites	[redacted]

The costs for the fuel cell stack, battery pack and hydrogen storage tank are derived from quotes given by the respective vendor. The total project budget is derived in accordance with the methodology presented in the Guide to the Project Management Body of Knowledge [24]. As such, a ± 25% estimate is applied to the total project budget as shown in Table XVII due to the preliminary nature of this project. Furthermore, this estimate accounts for the acquisition of a BMS and FCTMS. Note that project labor costs are not accounted for in the total project budget as this is outside the scope of this project.

TABLE XVII: TOTAL PROJECT BUDGET

	Cost (USD)	**Description**
Project Estimate	[redacted]	Total cost of major components
Contingency Reserve	[redacted]	15% applied to project estimate
Cost Baseline	[redacted]	Project estimate + Contingency reserve
Management Reserve	[redacted]	5% applied to project estimate
Total Project Budget	[redacted]	**Cost Baseline + Management Reserve**

The contingency reserve is added to the total project budget to account for potential risks that remain after risk response planning, whereas the management reserve is added to account any unforeseen risks or changes to the project.

Table XVIII presents the overall retail costs of Motor Coach Industries' main product lines.

TABLE XVIII: RETAIL PRICES OF MOTOR COACH INDUSTRIES' MAIN PRODUCT LINES [23]

Coach	**Retail Price (USD)**
Diesel	[redacted]
Compressed Natural Gas	[redacted]
Hybrid Diesel-Electric	[redacted]

With the total project budget, added development costs and retail markup, it is expected for the hydrogen fuel cell system to be on the expensive end of Motor Coach Industries' propulsion methods. However, the total price of the hydrogen fuel cell coach is expected to decrease with an increase in production volume, creating a beneficial tradeoff for future implementation.

4.6 Failure Modes and Effects Analysis

A FMEA is developed to identify critical failure modes of the hydrogen fuel cell system components and determine recommended actions to reduce the risk of critical failure modes. The FMEA consists of multiple parameters:

- The **Potential Failure Mode** is a potential scenario in which a component can fail.
- The **Potential Effect** is the effect that failure mode will have on internal and external customers.
- The **Severity Rating (SEV)** is a numerical rating determined by the severity of the potential effect.
- The **Potential Causes** are possible sources of the potential failure mode.
- The **Frequency Rating (FREQ)** is a numerical rating determined by the expected frequency or probability of the potential failure mode.
- The **Current Controls** are existing system controls that aid to prevent or detect the potential failure mode.
- The **Detection Rating (DET)** is a numerical rating determined by the existing ability to prevent or detect the potential failure mode.
- The **Risk Priority Number (RPN)** is a value used to evaluate the criticality of potential failure modes, obtained through the product of the severity rating, frequency rating and detection rating.
- The **Action Recommendations** are action that should be taken to improve upon potential failure modes and reduce their risk priority number.

The criteria for determining the severity rating, frequency rating and detection rating of potential failure modes are shown in Table XIX, Table XX and Table XXI respectively.

TABLE XIX: SEVERITY RATING CRITERIA

Severity Rating (SEV)	**Description**	**Criteria**
1-2	Very Low Severity	The system is undamaged and continues to operate. There are no safety risks.
3-4	Low Severity	The system is damaged but continues to operate with compromised efficiency. There are no safety risks.
5-6	Moderate Severity	The system component is damaged and the system cannot operate. There are no safety risks.
7-8	High Severity	The system component is damaged and the system cannot operate. No person is injured but there is potential for injury.
9-10	Very High Severity	Multiple components of the system are damaged and the system cannot operate. At least one person is injured.

TABLE XX: FREQUENCY RATING CRITERIA

Frequency Rating (FREQ)	**Description**	**Criteria**
1-2	Very Low Frequency	The failure mode is only likely to occur due to multiple specific external conditions.
3-4	Low Frequency	The failure mode is only likely to occur due to a single external condition.
5-6	Moderate Frequency	The failure mode is likely to occur regardless of external conditions. The failure mode would occur after 10,000 hours of normal operation.
7-8	High Frequency	The failure mode is likely to occur regardless of external conditions. The failure mode would occur after 1,000 hours of normal operation.
9-10	Very High Frequency	The failure mode is very likely to occur regardless of external conditions. The failure mode would occur after 100 hours of normal operation.

TABLE XXI: DETECTION RATING CRITERIA

Detection Rating (DET)	**Description**	**Criteria**
1-2	Very High Detectability	Systems are capable of automatically detecting the failure mode and fail-safes are in place to prevent the failure mode from worsening.
3-4	High Detectability	The failure mode can be manually detected and fail-safes are in place to prevent the failure mode from worsening.
5-6	Moderate Detectability	Systems are capable of automatically detecting the failure mode but no fail-safes are in place to prevent the failure mode from worsening.
7-8	Low Detectability	The failure mode can be manually detected but no fail-safes are in place to prevent the failure mode from worsening.
9-10	Very Low Detectability	There is no ability to detect the failure mode and no fail-safes prevent the failure mode from worsening.

Several potential failure modes pertaining to the final layout design were identified, and a severity, frequency, and detection rating was assigned to each of these risks. These ratings were assigned based on potential causes and effects, and as well current controls that aid in preventing or detecting said failure mode. Through this analysis, the three highest priority failure modes were identified to be failure of obtaining system's optimal fill pressure, particulate filter becoming heavily restricted, and leakage from hydrogen lines. The rest of the identified failure modes, and a detailed Failure Modes and Effects Analysis is presented in Table XXII.

With a RPN value of 180, it is a high possibility that the hydrogen fuel cell system will not be able to be filled to the working pressure of 700 bar. This would severely limit the range of the coach, as the coach would not be able to be filled to [redacted] hydrogen. This failure mode exists because of lack of fill station infrastructure that can provide [redacted] of hydrogen at a 700 bar working pressure. Currently, there are fill stations that operate at 700 bar but are intended for small vehicles that have much shorter ranges and hydrogen capacities. As such, this system will create a huge drain on this fill stations, and the system will not be able to be filled to its limit. Therefore, it is recommended that a market analysis be performed to evaluate feasibility of the system on the currently available fill stations. Additionally, it may also be possible to collaborate with current fill station suppliers to develop appropriate fill stations that can be placed on possible coach operation routes.

The second highest priority failure mode is determined to be the air intake particle filter becoming heavily restricted, reflected by a value of 126. This could potentially lead to the fuel cell stacks not generating enough power, leading to performance issues and degradation of coach overall range. A key cause of this issue would be prolonged use of the coach without regular filter replacements. Currently, the fuel cell stacks and batteries have in-built provisions for indicating this loss of power, so this would be an indication of a restricted intake. However, it is recommended that a preventative maintenance schedule be developed for replacing the particle filter, instead of relying on the power loss indication.

At a RPN value of 96, the third highest priority failure mode is major hydrogen leakage from hydrogen fittings. This would lead to hydrogen accumulating in the coach compartments, which poses a safety risk for coach passengers. A major cause for this leakage would be general wear and tear from prolong usage and vibrations. To disperse this leaked hydrogen to the atmosphere, safety vents are placed on the coach doors. Furthermore, the coach compartments are foam sealed to restrict hydrogen from entering the passenger cabin, thus the hydrogen is forced to exit the comportment through the safety vents. Sleeves on the fittings on the hydrogen piping further restrict hydrogen from leaking initially. In order to reduce the RPN number of this failure mode, it is recommended that sensors be placed throughout the coach compartment to detect leaked hydrogen, and which can execute purging of the hydrogen to the atmosphere and can alert the driver to begin evacuations.

TABLE XXII: FAILURE MODES AND RISK ANALYSIS

Rank	**Component**	**Potential Failure Mode**	**Potential Effect**	**SEV**	**Potential Causes**	**FREQ**	**Current Controls**	**DET**	**RPN**	**Action Recommendations**
1	Hydrogen Storage Tanks	[redacted]	The range of the coach will be limited	4	[redacted]	9	None	5	180	An analysis should be conducted on the feasibility of fueling the coach at existing fill stations. Collaborate with fill station vendors to develop appropriate fill stations along possible routes.
2	Intake Filter	The particle filter becomes heavily restricted	The fuels cell stacks produce limited power and range of the coach is reduced	3	Prolonged usage of the filter without replacement	6	The fuel cell would indicate that less power is being produced and the batteries would indicate a faster discharge rate	7	126	A preventative maintenance schedule should be developed for replacing the particle filter
3	Hydrogen Lines	Major leakage from fittings	Hydrogen accumulates in baggage bay	8	Prolonged usage and vibrations	3	Vents are located in the baggage compartment doors. Lines and baggage compartment are sealed.	4	96	Hydrogen -detection sensors should be placed throughout the coach compartments to detect hydrogen gas, purge the coach compartments to ambient atmosphere, and alert the driver. A maintenance schedule should be developed for fitting inspection.
4	Fuel Cell Exhaust	Exhaust water freezes	The internals of the fuel cell stack are damaged	8	Operating fuel cell coach in cold climate	1	None	10	80	A water collection system should be implemented to operate the coach in cold climate
5	Fuel Cell System	Corrosion	Oxidization may form on the components within the coach, leading to structural degradation	3	Minor constant hydrogen leakage may cause generation of water in the coach compartment	3	Lines and baggage compartments are sealed to minimize hydrogen leakage	7	63	Proper containment and maintenance schedule be developed to investigate structure for signs of oxidations in the coach.
6	Fuel Cell System	Major leakage from all components of the fuel cell system	Hydrogen accumulates in baggage bay and ignites Hydrogen leaks into passenger compartment and accumulates, displacing air	10	Vehicle accident	1	Vents are located in the baggage compartment doors. Lines and baggage compartment are sealed. Safety vent lining in the lining system. Emergency shut-off valves.	2	20	Hydrogen -detection sensors should be placed throughout the coach compartments to detect hydrogen gas, purge the coach compartments to ambient atmosphere, and alert the driver. Handheld fire suppression systems placed on board.
7	Fuel Cell Stack	Subpar performance	Fuel cell stacks' performance is compromised, leading to potential damage	3	Fuel cell stack vibrate due to repeated cyclical loading	4	None	5	60	Appropriate mounting hardware for mounting of the fuel cell stacks must be considered that minimizes vibrations

8	FCTMS	Cooling systems fail	Fuel cell stacks' performance is compromised, leading to potential damage	4	Cooling systems fail due to overexertion, or a random failure	2	None	5	40	A preventative maintenance schedule should be developed for the fuel cell thermal management system
9	BTMS	Cooling systems fail	Fuel cell stacks' performance is compromised, leading to potential damage	4	Cooling systems fail due to overexertion, or a random failure	2	None	5	40	A preventative maintenance schedule should be developed for the fuel cell thermal management system
10	Battery Pack	Spark Ignition	Fire may ignite due to corroded terminals, causing damage	8	Battery packs corrode	1	None	5	40	A preventative maintenance schedule should be developed for the battery pack. Handheld fire suppression systems placed on board. Sensors be placed to inform driver of high battery temperatures.
11	Hydrogen Lines	Major leakage from fittings	Hydrogen accumulates in baggage bay and ignites	10	Prolonged usage and vibrations. High temperatures in coach compartments.	1	Vents are located in the baggage compartment doors. Lines and baggage compartment are sealed. Thermal management systems regulate temperatures.	4	40	Hydrogen -detection sensors should be placed throughout the coach compartments to detect hydrogen gas, purge the coach compartments to ambient atmosphere, and alert the driver. Handheld fire suppression systems placed on board.
12	Hydrogen Lines	Major leakage from fittings	Hydrogen leaks into passenger compartment and accumulates, displacing air	10	Prolonged usage and vibrations	1	Vents are located in the baggage compartment doors. Lines and baggage compartment are sealed.	4	40	Hydrogen -detection sensors should be placed throughout the coach compartments to detect hydrogen gas, purge the coach compartments to ambient atmosphere, and alert the driver. Handheld fire suppression systems placed on board.
13	Storage Tanks	Storage tanks material fail	Hydrogen is expulsed in the coach compartments Hydrogen accumulates in baggage bay and ignites Hydrogen leaks into passenger compartment and accumulates, displacing air	10	Material failure due to cyclic loading from filling and draining	1	Vents are located in the baggage compartment doors. Lines and baggage compartment are sealed. Safety vent lining in the lining system. Emergency shut-off valves.	3	30	A preventative maintenance schedule should be developed for the storage tanks. [redacted]
14	Fuel Cell System	Impure hydrogen fuel	Overall system performance is reduced, and may lead to component damage	6	Impure hydrogen filled in the system at a filling station	1	Defueling and sampling ports in the hydrogen lines to purge or test the hydrogen fuel	4	24	Ensure fill station supplier complies with safety and quality standards
15	Fuel Cell System	Fuel cell system components unavailable	Overall system specifications may change, and system cost will be affected	2	Vendor company may go bankrupt	2	None	1	4	Source multiple vendors for the specified fuel cell system products

4.7 Final Design Evaluation

This section evaluates the metrics of the final design, as established in Table VI. Each metric is evaluated based on the extent to which the metric achieves its ideal value, as shown in Table XXIII. The evaluation is color coded, with green indicating a metric meeting its ideal value, yellow indicating a metric exceeding its marginal value but failing to meet its ideal value and red indicating a metric failing to meet its marginal value.

TABLE XXIII: EVALUATION OF FINAL DESIGN

#	Metric	Imp.	Units	Marginal Value	Ideal Value	Needs Addressed	Actual Value
1	Ease of accessibility of hydrogen fuel cell components	4	subj.	-	Board Approval	4, 8	Board Approval
2	All applicable standards met	5	binary	-	Yes	1, 2	Yes
3	The selected design adequately prevents hydrogen leakage from entering the cabin	5	subj.	-	Board Approval	2	Board Approval
4	The selected design is easily integrated into the current coach layout	4	subj.	-	Board Approval	5	Board Approval
5	The range that the hydrogen fuel cell coach can achieve at a constant speed of 96.6 km/h	5	hours	>8	>10	3	7
6	Number of baggage bays available	3	int.	>0	>1	7	1
7	Reasonable considerations are given to keep hydrogen fuel cell system costs low	3	subj.	-	Board Approval	9	Board Approval
8	The weight distribution of the hydrogen fuel cell system is adequately similar to that of the battery-electric system	3	subj.	-	Board Approval	6	Board Disapproval

Metric two, the only binary metric, is evaluated as a success. The final design adheres to all applicable standards, as all core components and auxiliary components within the hydrogen fuel cell system are rated as required. All the applicable standards are summarized in Table VII and Table VIII, while specifications for all components are listed in Section 2.

Metric five and six, the quantitative metrics, are evaluated as a failure and a marginal success, respectively. Metric five is evaluated as a failure since the range of the hydrogen fuel cell system is seven hours, which is less than its marginal value of eight hours. However, the current range is acceptable as an increase in the range is rendered infeasible by the number of hydrogen storage tanks, which are at their maximum capacity within the confines of the J4500e coach. Metric six is evaluated as a marginal success since compartment three within the J4500e coach is utilized as a baggage compartment, while the remaining compartments are utilized for the hydrogen fuel cell system.

Metric one, three, four, seven and eight are all subjective metrics. These metrics were evaluated by five subject matter experts within Motor Coach Industries' engineering board. The success of each subjective metric is dependent on a unanimous approval by all members on the board. Metrics one, three, four and seven achieved a unanimous approval, therefore, these metrics are evaluated as a success. Reflective of metric one, all components within the hydrogen fuel cell system are relatively accessible to persons on the interior and exterior of the coach for maintenance purposes. Reflective of metric three, the hydrogen [redacted], with adequate fittings to monitor internal conditions and safety lines to purge all hydrogen fuel during an emergency. Reflective of metrics four , the final design layout is able to be easily integrated into the coach layout with minimal modification to the existing J4500 frame. Reflective of metric seven, all reasonable considerations were given to the keep the cost of the hydrogen fuel cell system low.

Metric eight failed to gain approval of the board. This metric requires that the weight distribution of the hydrogen fuel cell system is adequately similar to that of the battery-electric coach. The final design's relative center of gravity (CG) is 2.14 m ahead of the CG of battery-electric coach and is 1648.8 kg lighter than the battery-electric coach. The board expressed concerns that even with the weight reduction, it is possible that the coach would become too front heavy with this design and would not be able to achieve the required axle ratings which are federally defined. It was recommended that a more detailed analysis be performed to determine the actual CG of the entire coach while considering the unsprung and sprung mass on the coach to determine the actual axle ratings. Determining accurate axle weight ratings of the coach is complex, as each axle operates on individual independent suspension, which is able to be adjusted to the required axle weights accordingly. This analysis was deemed out of scope for this project, and it is recommended that this analysis be performed for future feasibility study for the implementation of this project. Furthermore, the highest design priority was placed on maximizing the range of the coach, and the final design reflects this design decision. For future work, the CG of the final design may be able to be adjusted if range is not chosen as high of a priority i.e. by removing hydrogen storage tanks and increasing space to move heavier components such as the fuel cell stacks around.

Overall, as the final design attains ideal values for five of its eight metrics and attains a marginal value for one of its eight metrics, this project is deemed a success.

5. Recommendations

This section discusses recommendations for areas of improvement in the final hydrogen fuel cell system layout design, as well as any future work that must be addressed within the design.

The weight distribution analysis performed in this report only considered the CG location of the fuel cell system components relative to that of the battery-electric coach components. This was done to ensure that the axle weights of the hydrogen fuel cell coach remain similar to that of the electric coach. The weight on each axle of a coach is federally defined, and these axle ratings must be under this defined threshold for the coach to be road legal. The removal of the old batteries from the rear and front of the electric coach, and the addition of the hydrogen fuel cells and hydrogen storage tanks shifts the relative CG of the final design to 2.14 m ahead of the CG of the electric coach. As mentioned previously, this final design fails to meet this CG metric as the board disapproved with the CG of the final design being adequately similar to the battery-electric coach. Thus, it is recommended that as future work, the CG analysis of the entire coach with the hydrogen electric system be performed to determine if the coach complies with the appropriate axle ratings. It is possible to obtain a better CG placement of the final design, but due to the design requirement of maximizing range, the final design is the optimal solution for the established priorities.

The fill panel of the hydrogen fuel cell coach is derived from [redacted] Appropriate fittings and tubing for its modification have been defined in this report, however, a few more adjustments will need to be made to accommodate the presence of the two fuel cell stacks. This includes addition of two more pressure gauges, as well as defueling ports on the fill panel for the second fuel cell stack.

The hydrogen [redacted] for both low- and high-pressure sides, as this size minimized pressure losses in the system. A more rigorous analysis needs to be performed to increase confidence in the structural ability of the tubing to handle [redacted], and to the determine the appropriate pressure losses across various points in the system. [redacted]

[redacted] Using these input parameters, an appropriate hydrogen piping diameter could be calculated. Due to time constraints, the team could not establish a strong contact with any fill station supplier that could provide such information, and it is recommended that this be the first step to verify [redacted]

The operating temperature range of GC Valves Solenoid valve S401GF02C1BF5 is 0°C to 40°C [19]. This solenoid valve is used to remotely shut down flow of the hydrogen fuel into the fuel cell stacks in case of emergency and is the same one utilized by New Flyer Industries in their hydrogen fuel cell system. The final design was established based on the assumption that the system will be operated in California, and the solenoid valve's temperature range fits within this the temperature range in California. However, this valve will need to be replaced if the system is operated in a colder climate, such as in Canada and some other parts of the United States. Furthermore, operation in colder climates will require further modifications of the system, as a water collection system will need to be implemented in the exhaust of the fuel cell stacks. This is because in colder climates the expulsion of water onto the ground from the exhaust will create ice on roadways. This will need to be addressed by a water collection system on board the coach that will collect the water from the exhaust during its entire operation. This water collection system will then need to be drained after every trip.

Due to the preliminary nature of this project, it is recommended that numerous monitoring sensors be placed on all the hydrogen lines in the system during testing. These sensors would include pressure and temperature transducers to indicate the overall health of the system, and hydrogen leak detectors to shut down the system in case of a detected leak. An entire control system could be designed this way to automate the entire system and ensure the fuel cells are always receiving adequate amount of hydrogen.

Modifications to the existing structure between compartment three and four may be needed to accommodate the tubing section through those two compartments. This concern was brought up by the board members in the final design evaluation meeting. Currently, that part of the coach is being modified for other design considerations, and the final modifications has not been reflected in the CAD models of the overall frame of the coach. This area of the hydrogen fuel cell system may need to be re-visited as new information becomes apparent.

As this was a mechanically oriented project, most of the project focus was on placement of the components, and performance of the hydrogen fuel cell system as whole. It was assumed the electrical components, such as the provided batteries, would operate as intended and the specifics weren’t considered. However, it was discovered that fuel cell stacks may not generate enough voltage to power the specified batteries in the final design evaluation meeting. The board members expressed this concern and mentioned that an external inverter may be required to meet the voltage requirements of the batteries. It is recommended that this requirement should be analyzed further to ensure that the hydrogen fuel cell system will operate to the specification as described in this report.

6. SUMMARY

The purpose of this project was to integrate the layout of a hydrogen fuel cell system within Motor Coach Industries' J4500e electric coach chassis. Nine customer needs were determined in partnership with Motor Coach Industries to establish the priorities of design parameters. The most important needs, with an importance value of five, were to follow all applicable standards, protect against hydrogen leakage into the cabin, and maximize the range of the coach. The next most important needs, with an importance value of four, were to allow for ease of access for maintenance and facilitate the integration of the design into the current coach layout. Finally, the needs with an importance value of three were to maintain appropriate weight distribution, maximize baggage space, allow for easy installation of the system, and be sufficiently cost-effective.

The final design of the hydrogen fuel cell system consists [redacted], seven XMP76P battery modules from XALT Energy, and [redacted] as the major components. These major components were selected and optimally arranged within the frame of the coach through the concept development phase of the project. In the final design stage of the project, the air intake and exhaust piping were routed for the fuel cell stacks and the hydrogen lines were routed throughout the hydrogen fuel cell system with appropriate routing components.

The final design successfully meets most of the customer needs. The design was well integrated into the current coach layout, all applicable standards were followed, adequate consideration were made to protect against hydrogen leakage into the cabin, and the design allows for adequate maintenance access and ease of installation. However, to allow for baggage space to be maximized, the range of the range of the coach was compromised, only allowing the coach to achieve a highway haul of 7 hours. Additionally, the board of stakeholders believed that a more thorough analysis of the system's weight distribution could have been conducted to satisfy axle ratings.

Recommendations were developed to address unsatisfied needs and future developments of the project that were out of scope. The final design of this project in combination with the recommendations serve as a foundation for the further development of the hydrogen fuel cell system with Motor Coach Industries.

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APPENDIX A: DETAILED CUSTOMER NEEDS

Appendix A contains detailed information regarding the customer needs defined in Section 1.2.

Need 1: The Hydrogen Fuel Cell System Follows all Applicable Standards and Adheres to all Applicable Regulations

Need one is determined based on industry requirements. It is advised that all vehicles follow automotive standards and all hydrogen-powered vehicles follow hydrogen-powered vehicle standards, as a general guideline. It is required that all vehicles adhere to automotive regulations and all hydrogen-powered vehicles adhere to hydrogen-powered vehicle regulations to be deemed road-worthy. The selected design must abide by these standards and regulations. This need is given an importance value of five.

Need 2: The Hydrogen Fuel Cell System Cannot Leak into the Cabin

Need two is determined in conjunction with Motor Coach Industries. Since the hydrogen fuel cell system will primarily be located directly below the passenger cabin, it is important that any leaking hydrogen is sealed from entering the cabin to keep all passengers safe. This need is given an importance value of five.

Need 3: The Hydrogen Fuel Cell System Maximizes Range of the Coach

Need three is determined in conjunction with Motor Coach Industries. Since the hydrogen fuel cell coach will be designed for long range applications, maximizing the range of the fuel cell coach is crucial. Additionally, hydrogen fill stations are not a commonality, thus it is important that the hydrogen fuel cell coach maximizes range such that the coach can reach re-fueling stations before running out of fuel. This need is given an importance value of five.

Need 4: The Hydrogen Fuel Cell System Components are Easy to Access for Maintenance

Need four is determined in conjunction with New Flyer Industries' hydrogen fuel cell system. Many of the system's components require regular preventative maintenance to ensure the long service life and safety of the system. For these reasons, it is important that the system's components are easy to access, thus an importance value of four is given.

Need 5: The Hydrogen Fuel Cell System is Easily Integrated into the Current Coach Layout

Need five is determined in conjunction with Motor Coach Industries. It is a priority that the selected hydrogen fuel cell system components fit properly within the frame of the existing battery-electric coach, including all auxiliary components. This need is given an importance value of four.

Need 6: The Hydrogen Fuel Cell System has Appropriate Weight Distribution

Need six is determined in conjunction with Motor Coach Industries. It is important that the weight of the fuel cell system is properly balanced to maximize the stability and handling of the coach. The components of the fuel cell system must be properly arranged to contribute toward proper weight distribution of the coach and meet the load ratings for each axle. This need is given an importance of three.

Need 7: The Hydrogen Fuel Cell System Maximizes Baggage Space

Need seven is determined in conjunction with Motor Coach Industries. It is important to Motor Coach Industries that baggage space is maximized to exploit the utility of the coach. Therefore, the fuel cell system must be configured in a manner which maximizes baggage space. This need is given a priority value of three.

Need 8: The Hydrogen Fuel Cell System is Easy to Install

Need eight is determined based on the nature of the manufacturing environment in which the system must be utilized. It is important that the fuel cell system is easy to install in order to minimize the time required for installation, minimize the complexity of the installation process and minimize the types of tools and fixtures required for installation. This need is given an importance value of three.

Need 9: The Hydrogen Fuel Cell System is Cost-Effective

Need nine is determined in conjunction with Motor Coach Industries. The development of the fuel cell coach is in its early stages, with no preliminary cost figures. However, cost-effectiveness must be considered in the design and selection of the hydrogen fuel cell system's components. This need is given an importance value of three.

APPENDIX B: DETAILED CONSTRAINTS AND LIMITATIONS

Appendix B contains detailed information regarding the constraints and limitations defined in Section 1.3.

Constraint 1: Cost-Effective Design

Although no definitive budget has been enforced, the hydrogen fuel cell system must be a cost-effective design in comparison to other power methods within Motor Coach Industries' product lines, including diesel, compressed natural gas and hybrid diesel electric powered coaches. The total cost of these coaches [redacted] for the diesel, compressed natural gas and hybrid diesel electric powered coaches, respectively. All currency figures are in USD.

Constraint 2: Timeline of Project

With the deadline of the final report on December 6th, 2018, the team must balance all tasks through intensive scheduling and delegating in order to complete the project and all required deliverables within time constraints.

Constraint 3: J4500e Coach Space Availability

The J4500e coach has a finite amount of space within the framework of its body that is available for the implementation of the hydrogen fuel cell system. Therefore, all components within the hydrogen fuel cell system must adhere to spacing requirements.

Constraint 4: Battery Pack Requirements

All battery packs employed in the analysis of this project are those provided by XALT Energy. The vendor, XALT Energy, is selected as the sole provider of the battery packs as the company has an established relationship with Motor Coach Industries.

Constraint 5: Fuel Cell Requirements

All hydrogen fuel cell stacks employed in the analysis of this project are those provided by Ballard Power Systems. The vendor, Ballard Power Systems, is selected as the sole provider of the fuel cell stacks as the company has an established relationship with Motor Coach Industries.

Constraint 6: Hydrogen Storage Tank Selection

All tanks employed in the analysis of this project are those provided by Hexagon Composites, in conjunction with New Flyer Industries. The vendor, Hexagon Composites, is selected as the sole provider of the hydrogen storage tanks as the company has an established relationship with New Flyer Industries, the parent company of Motor Coach Industries.

Constraint 7: Total Power Requirements

The average total power required is between 70kW to 170kW for the J4500e coach. Although the power requirements are dependent on the combined draw of the propulsion motor in conjunction with all accessories, the fuel cell system must accommodate the stated power range.

Constraint 8: Compatibility

The hydrogen fuel cell system must be compatible with the J4500e coach, with all components seamlessly integrating into the existing coach. This constrains the hydrogen fuel cell components to those compatible with the J4500e coach.

Constraint 9: Maintenance and Accessibility of Fuel Cell Stack

The hydrogen fuel cell stack must be accessible to persons on the interior and exterior of the coach for maintenance purposes. The general maintenance schedule for all cell stacks are in Appendix C.

Constraint 10: Range of Operation

The hydrogen fuel cell system must be functional within both city and highway driving conditions, given a continuous operation time of ten hours. Additionally, hydrogen the fuel cell system must remain operational in fluctuating weather conditions, specifically [redacted]

Constraint 11: Standards

The hydrogen fuel cell system must adhere to all applicable standards including high voltage, fuel storage system, storage tank, tank valve, thermal pressure relief, fuel handling system, fill receptacle, air intake system, air exhaust system, cooling system and J4500e standards.

APPENDIX C: [redacted] SERVICE SCHEDULE

Appendix C contains the [redacted] service schedule. The values listed are applicable to all the fuel cell stacks provided by Ballard Power Systems including the [redacted]

[redacted]

APPENDIX D: DETAILED METRICS

Appendix D contains detailed information regarding the customer needs defined in Section 1.4.

Metric 1: Ease of accessibility of hydrogen fuel cell components

Metric one is subjective and addresses both needs four and eight. It states that the system provides ease of access for maintenance and that the system is easy to install. The ideal value is to gain approval from the board of stakeholders. This metric is given an importance value of four to correspond with the needs it addresses.

Metric 2: All applicable standards met

Metric two is binary as it evaluates whether the required automotive standards and hydrogen-powered vehicle standards are met by the design of the fuel cell system. This metric addresses need one, that all applicable standards are met; and need two, that the fuel cell system cannot leak into the cabin. Any standards that constrain the design of the fuel cell system must be determined and followed. This metric is given an importance value of five to correspond with the needs it addresses.

Metric 3: The selected design adequately prevents hydrogen leakage from entering the cabin

Metric three is subjective and addresses need two, that the fuel cell system cannot leak into the cabin. This metric evaluates measures taken to prevent possible hydrogen leakage from entering the cabin beyond what is required by hydrogen-powered vehicle standards. The ideal value is to gain approval from the board of stakeholders. This metric is given an importance value of five to correspond with the need it addresses.

Metric 4: The selected design is easily integrated into the existing current coach layout

Metric four is subjective and addresses need five, that the fuel cell system is easily integrated into the current coach layout. The ideal value is to gain approval from the board of stakeholders. This metric is given an importance value of four to correspond with the need it addresses.

Metric 5: The range that the hydrogen fuel cell coach can achieve at a constant speed of 96.6 km/h

Metric five is quantitative and addresses need three, that the range of the coach is maximized. Optimizing the selection and placement of the fuel cell stack, battery pack, and fuel tank systems maximizes the range that the coach can achieve at a constant speed of 96.6 km/h. The marginal value is to achieve a range of at least eight hours, and the ideal value is to achieve a range of at least 10 hours. This metric is given an importance value of five to correspond with the need it addresses.

Metric 6: Number of baggage bays available

Metric six is quantitative and addresses need seven, that baggage space must be maximized by the design of the fuel cell system. The selected components for the fuel cell system must be arranged to maximize the amount of baggage space maintained. The marginal value is to have at least some room dedicated to baggage space underneath the coach, and the ideal value is to have at least one full baggage bay remain available. This metric is given an importance value of three to correspond with the need it addresses.

Metric 7: Reasonable considerations are given to keep hydrogen fuel cell system costs low

Metric seven is subjective and addresses need nine, that the fuel cell system is cost-effective. The ideal value is to gain approval from the board of stakeholders. This metric is given an importance value of three to correspond with the need it addresses.

Metric 8: The weight distribution of the hydrogen fuel cell system is adequately similar to that of the battery-electric system

Metric eight is subjective and addresses need six, that the fuel cell system has appropriate weight distribution. The components of the fuel cell system must be properly arranged to meet the specific axle ratings. The ideal value is to gain approval from the board of stakeholders. This metric is given an importance value of three to correspond with the need it addresses.

APPENDIX E: FUEL CELL STACK SPECIFICATIONS

Appendix E contains specifications for the [redacted] and [redacted]

APPENDIX E: LIST OF FIGURES

E2

[redacted]

Figure E2. HD60, HD85 and HD100 fuel cell stack specifications (Sheet 1/2) [4]

[redacted]

Figure E3. HD60, HD85 and HD100 fuel cell stack specifications (Sheet 2/2) [4]

APPENDIX F: BATTERY PACK SPECIFICATIONS

Appendix F contains specifications for the XMP76P battery modules.

APPENDIX F: LIST OF FIGURES

[redacted]

Figure F1. XMP76P battery module specifications (Sheet 1/2) [5]

[redacted]

Figure F2. XMP76P battery module specifications (Sheet 2/2) [5]

Appendix G: Hydrogen Storage Tank Specifications

Appendix G contains specifications for the hydrogen storage tanks.

Appendix G: List Of Figures

HEXAGON

HYDROGEN STORAGE AND TRANSPORTATION SYSTEMS

TYPE 4 HYDROGEN CYLINDERS

Hexagon Composites is a globally leading supplier of Type 4 high-pressure composite cylinders and systems for storage and transport of various gases under pressure. Type 4 tanks are the best combination of safety, efficiency and durability available. Their lightweight construction improves vehicle range, payload and handling.

Hexagon Composites is well positioned across the hydrogen value chain with vehicle tanks for cars and buses, ground storage, transportation and backup power solutions. Development and production take place at modern facilities in Lincoln, Nebraska (US), Kassel (Germany) and Raufoss (Norway).

FUEL CELL VEHICLES
Hexagon Composites has developed high-pressure hydrogen cylinders for fuel cell vehicles, which are fueled by hydrogen and produce no harmful emissions when operating.

GROUND STORAGE
The introduction of fuel cell vehicles will drive the demand for Hydrogen refueling stations (HRS). The fatigue-resistant cycling properties of composite pressure cylinders make them more suitable for storage than steel alternatives.

GAS DISTRIBUTION
Demand for Hydrogen distribution solutions will grow strongly as a function of the demand for transportation of hydrogen from renewable sources. Hexagon Composites' Mobile Pipeline® and X-STORE® solutions are certified for Hydrogen distribution. Type 4 tanks allow more gas to be transported in a given trailer space.

BACKUP POWER
Hydrogen fuel cells are an efficient and emerging choice for low-emission, reliable backup power used for telecommunications, emergency services and in remote locations. Hexagon Composites offers backup power solutions with lightweight Hydrogen tanks that enhance system performance and payback.

MARINE AND RAIL
Hexagon Composites is at the forefront of developing hydrogen solutions for the marine and rail industry.

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Norway: +47 70 30 44 50
Germany: +49 561 585 49-0
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Figure G1. Hexagon Composites hydrogen storage tank specifications (Sheet 1/2) [6]

HEXAGON COMPOSITES HYDROGEN TYPE 4 CYLINDER INFORMATION

Type 4 cylinders designed and manufactured by Hexagon Composites' wholly owned subsidiaries Hexagon Lincoln, Hexagon Raufoss and Hexagon xperion.

REF	NOMINAL WORKING PRESSURE (15° C) MPa	OUTSIDE DIAMETER MM	OVERALL LENGTH MM	WEIGHT KG	WATER VOLUME L	HYDROGEN CAPACITY KG
A*	20	315	1 060	16	46	0.7
B	25	541	2 783	164	450	8.0
C	25	503	2 342	94	350	6.0
D	30	509	2 342	112	350	7.2
E	35	420	3 190	101	312	7.5
F	35	509	2 342	112	350	8.4
G	50	565	3 277	280	530	16.5
H	50	531	2 424	229	347	10.7
I	70	319	906	34	36	1.4
J	70	238	1 600	29	39	1.6
K	70	420	845	43	64	2.6
L	70	440	1 050	59	76	3.1
M	95	515	2 783	365	254	12.4

Figure G2. Hexagon Composites hydrogen storage tank specifications (Sheet 2/2) [6]

APPENDIX H: TUBING SPECIFICATIONS

Appendix H contains specifications for all tubing within the hydrogen fuel cell system.

APPENDIX H: LIST OF FIGURES

[redacted]

Figure H1. Swagelok tubing specifications (Sheet 1/3) [7]

[redacted]

Figure H2. Swagelock tubing specifications (Sheet 2/3) [7]

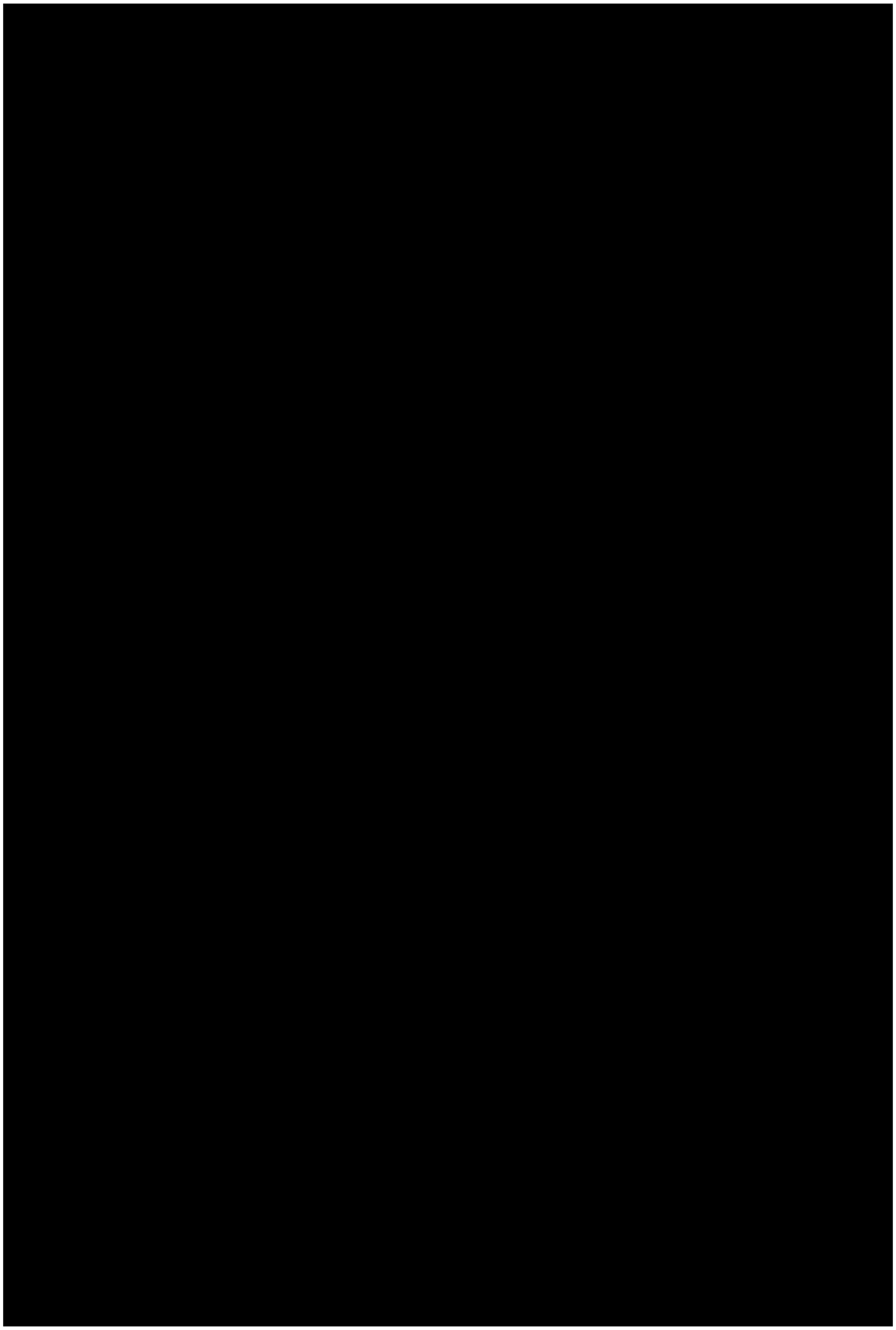

Figure H3. Swagelock tubing specifications (Sheet 3/3) [7]

APPENDIX I: COMPONENT SPECIFICATIONS

Appendix I contains specifications for all components within the hydrogen fuel cell system.

APPENDIX I: LIST OF FIGURES

[redacted]

Figure I1. WEH high and low pressure check valve specifications [8]

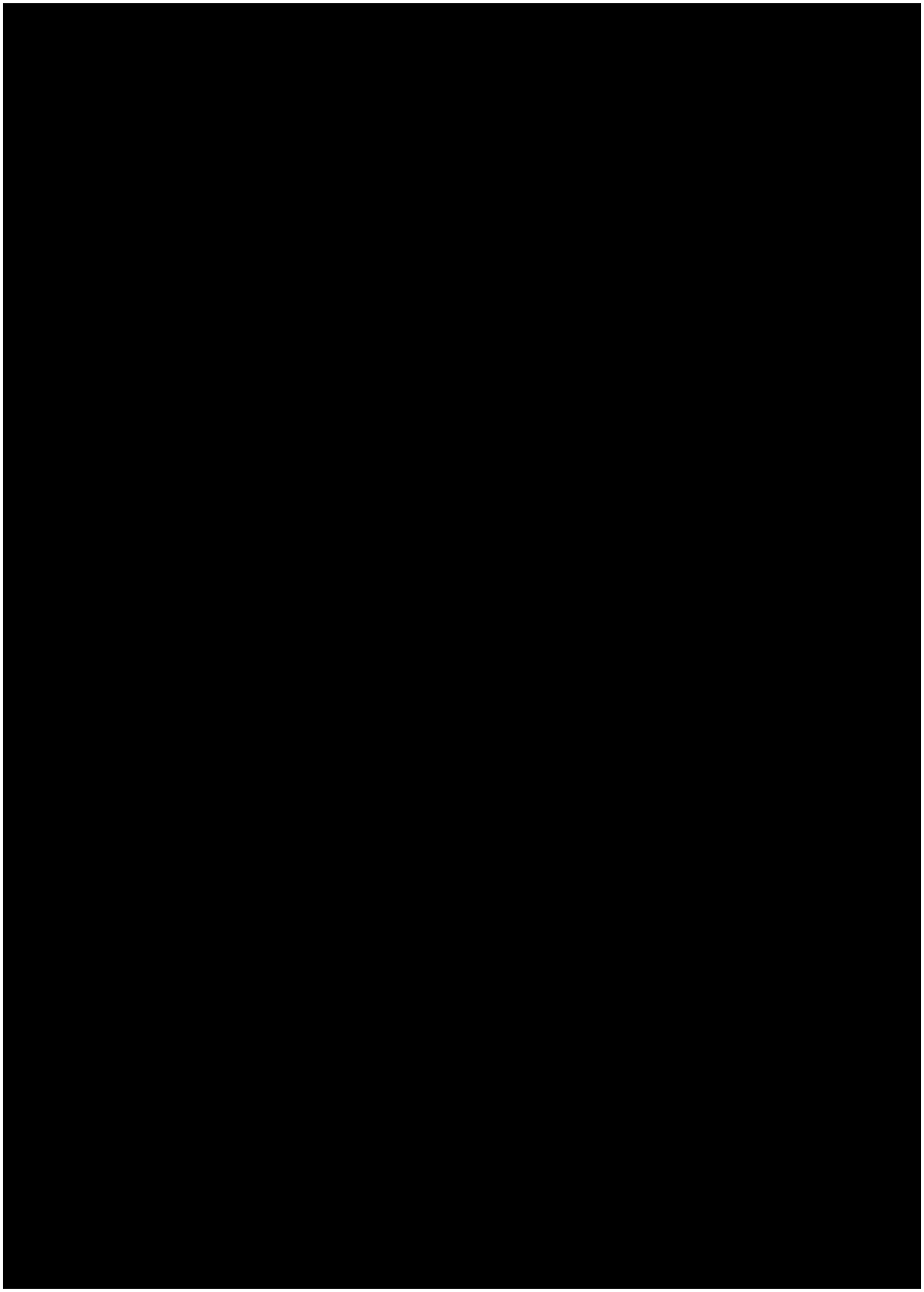

Figure I2. WEH high pressure fill receptacle [8]

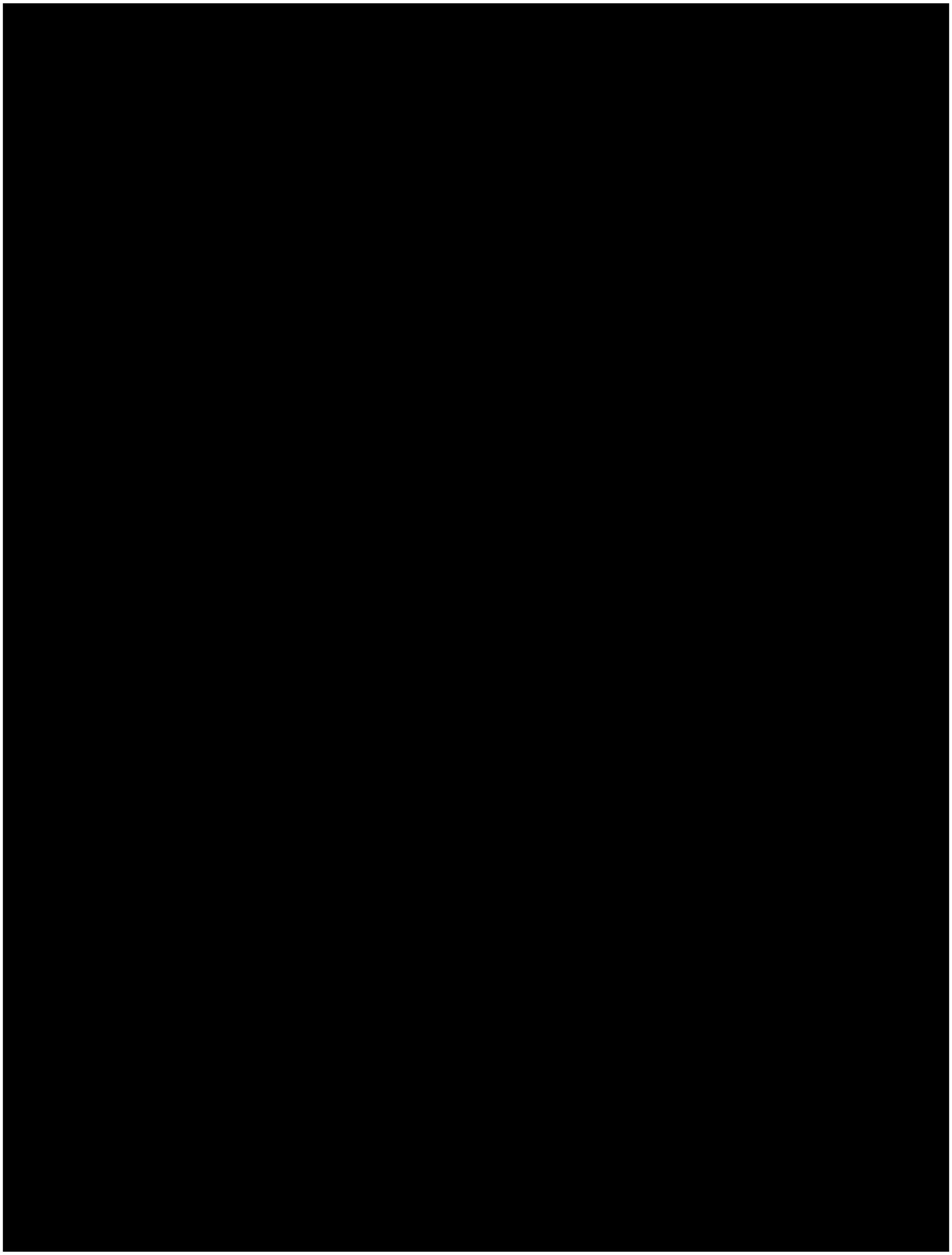

Figure I3. Swagelok high pressure hand shut-off plug valve [9]

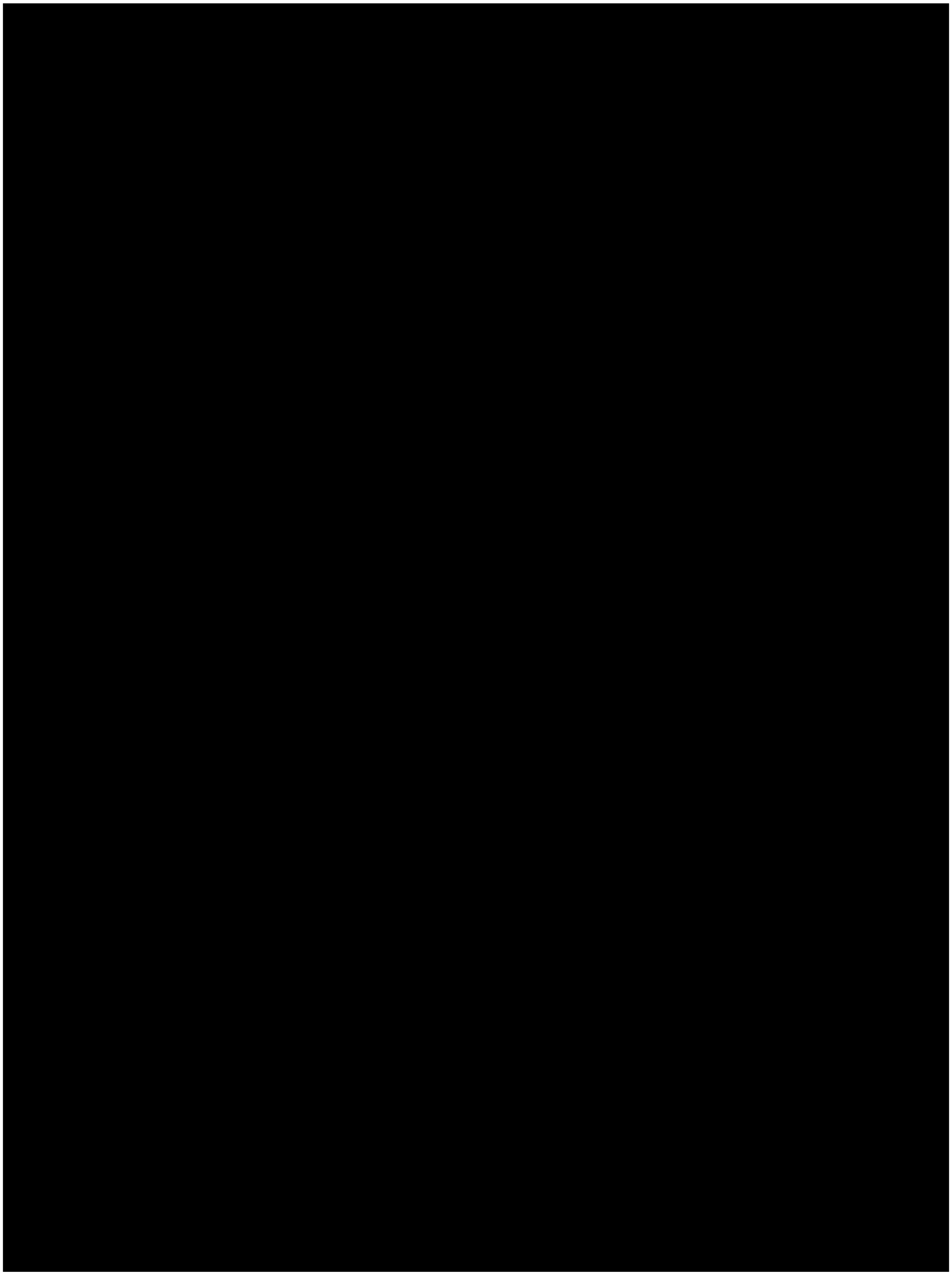

Figure I4. Swagelok low pressure hand shut-off plug valve [9]

[redacted]

Figure I5. Swagelok low pressure needle valve (Sheet 1/2) [10]

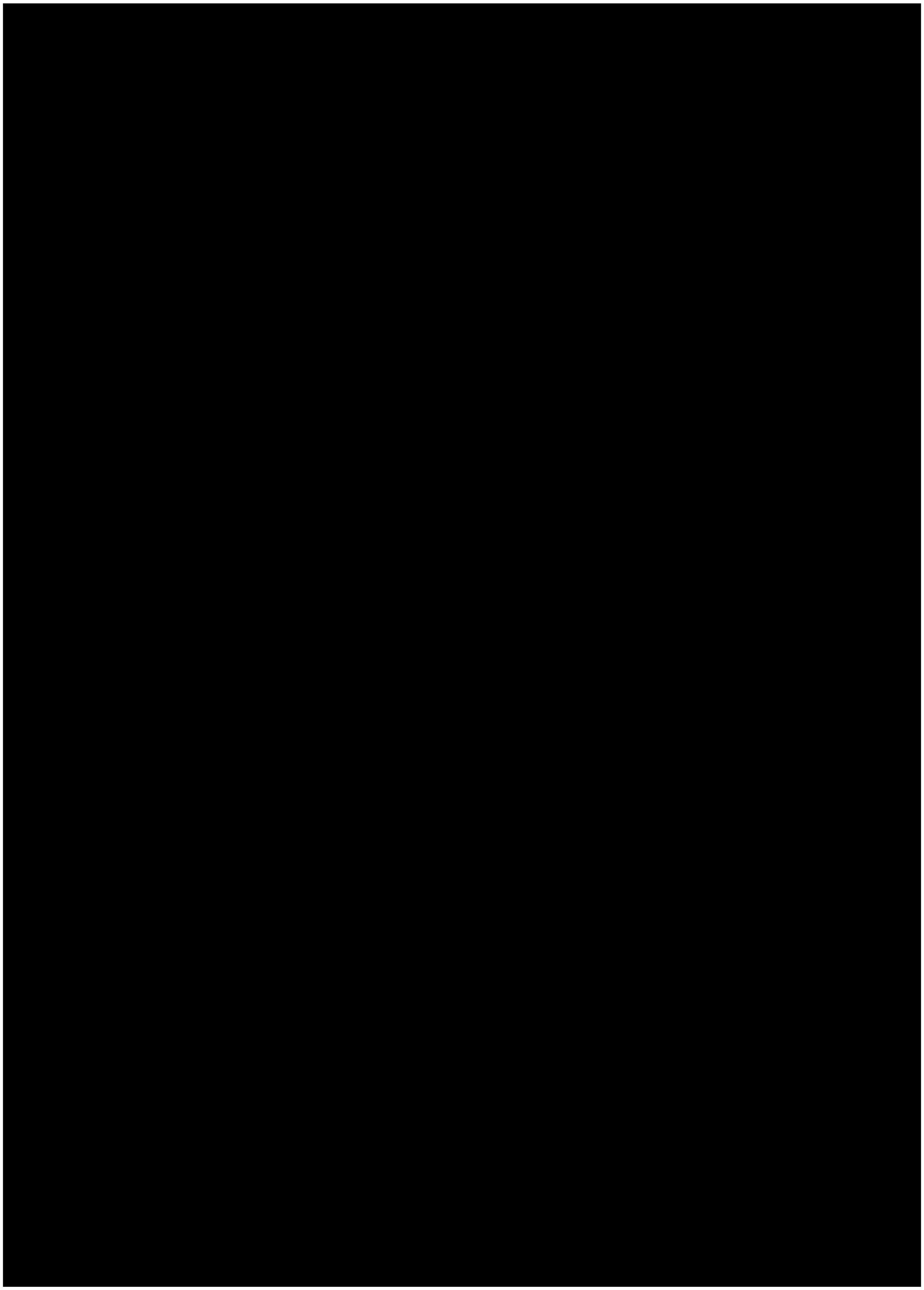

Figure I6. Swagelok low pressure needle valve (Sheet 2/2) [10]

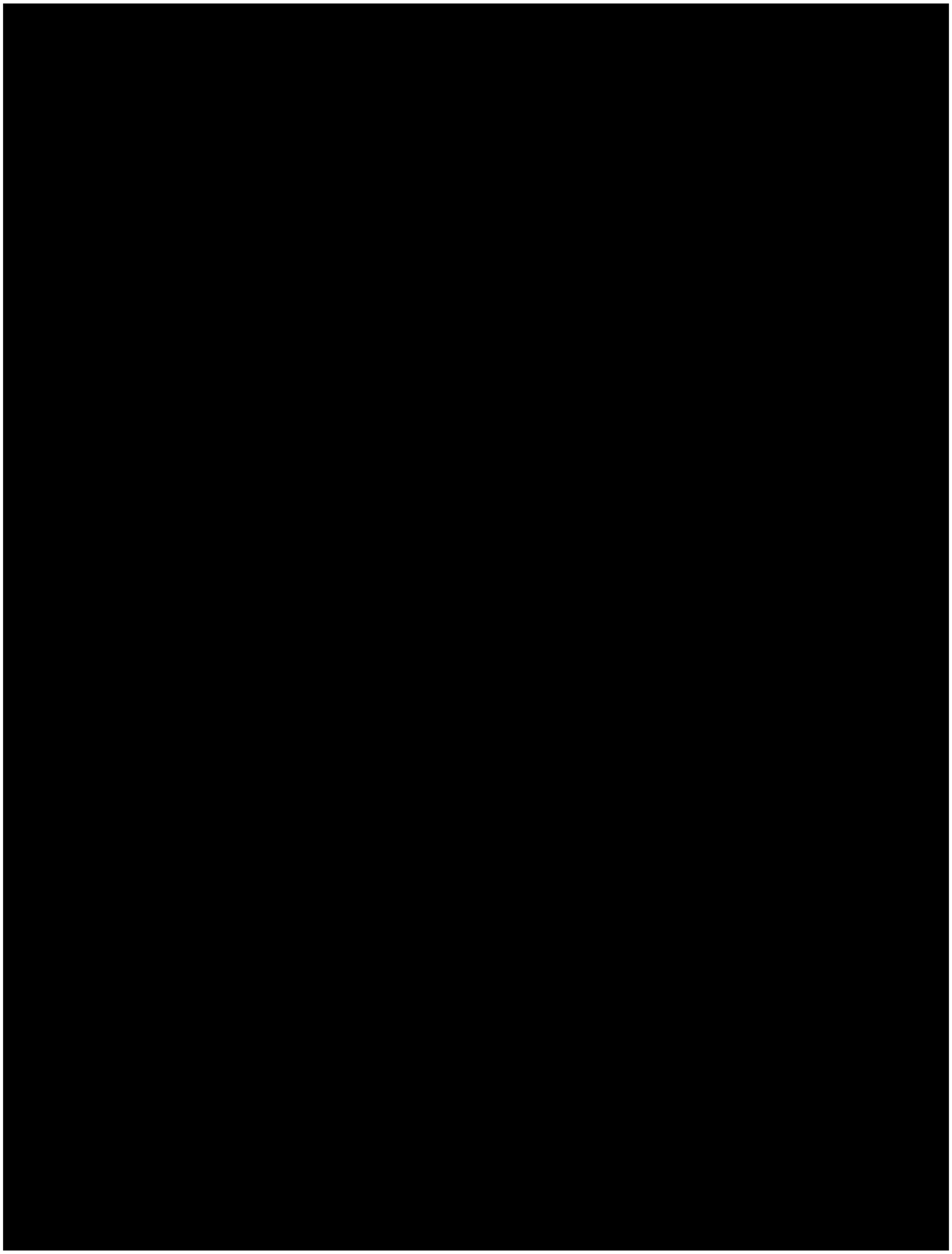

Figure I7. Swagelok high pressure particle filter [11]

[redacted]

Figure I8. Parker high pressure port quick connect (Sheet 1/3) [12]

[redacted]

Figure I9. Parker high pressure port quick connect (Sheet 2/3) [12]

[redacted]

Figure I10. Parker high pressure port quick connect (Sheet 3/3) [12]

[redacted]

Figure I11. Swagelok low pressure port quick connect (Sheet 1/2) [13]

[redacted]

Figure I12. Swagelok low pressure port quick connect (Sheet 2/2) [13]

[redacted]

Figure I13. Swagelok high pressure gage (Sheet 1/2) [14]

[redacted]

Figure I14. Swagelok high pressure gage (Sheet 2/2) [14]

[redacted]

Figure I15. Swagelok low pressure gage (Sheet 1/2) [14]

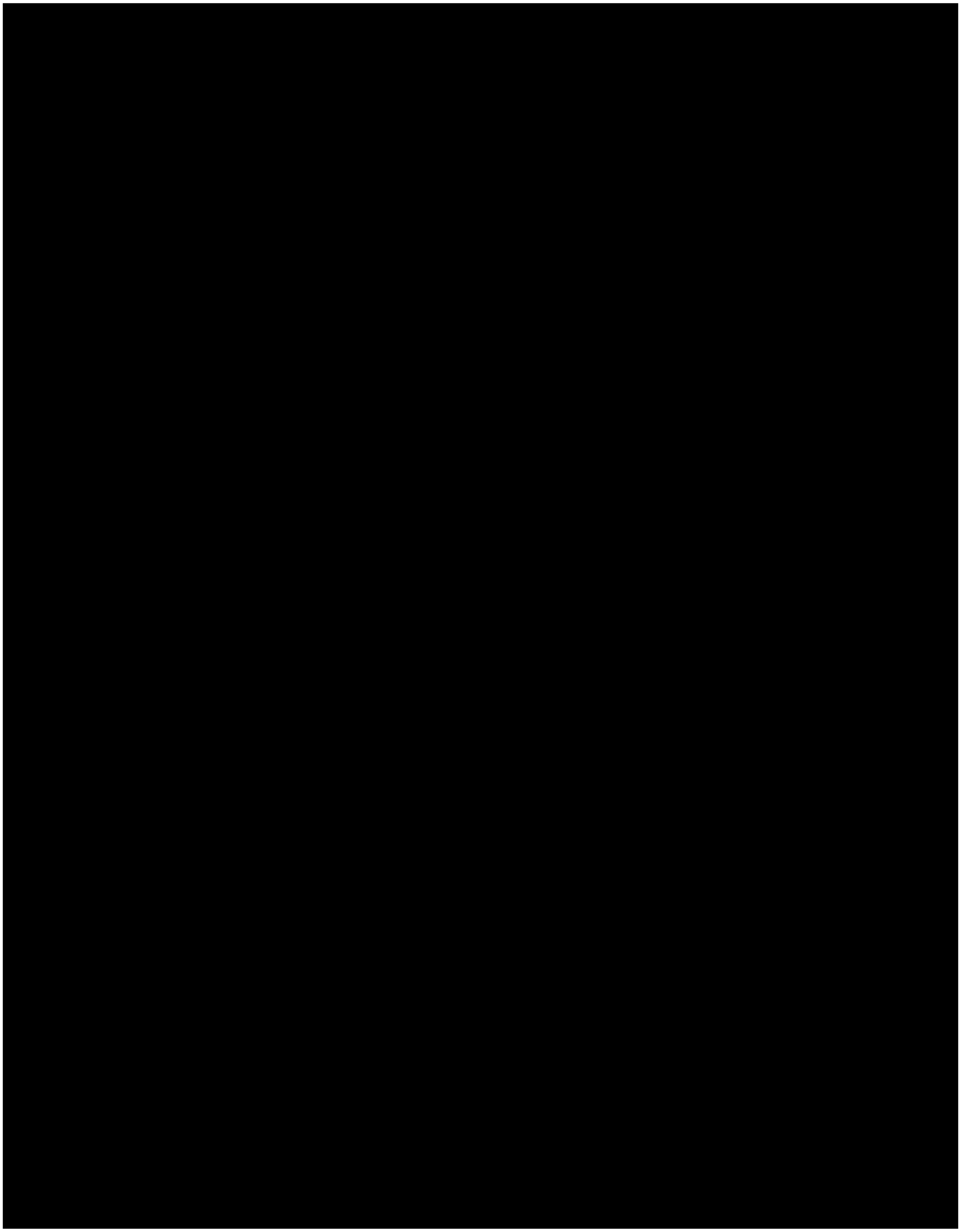

Figure I16. Swagelok low pressure gage (Sheet 2/2) [14]

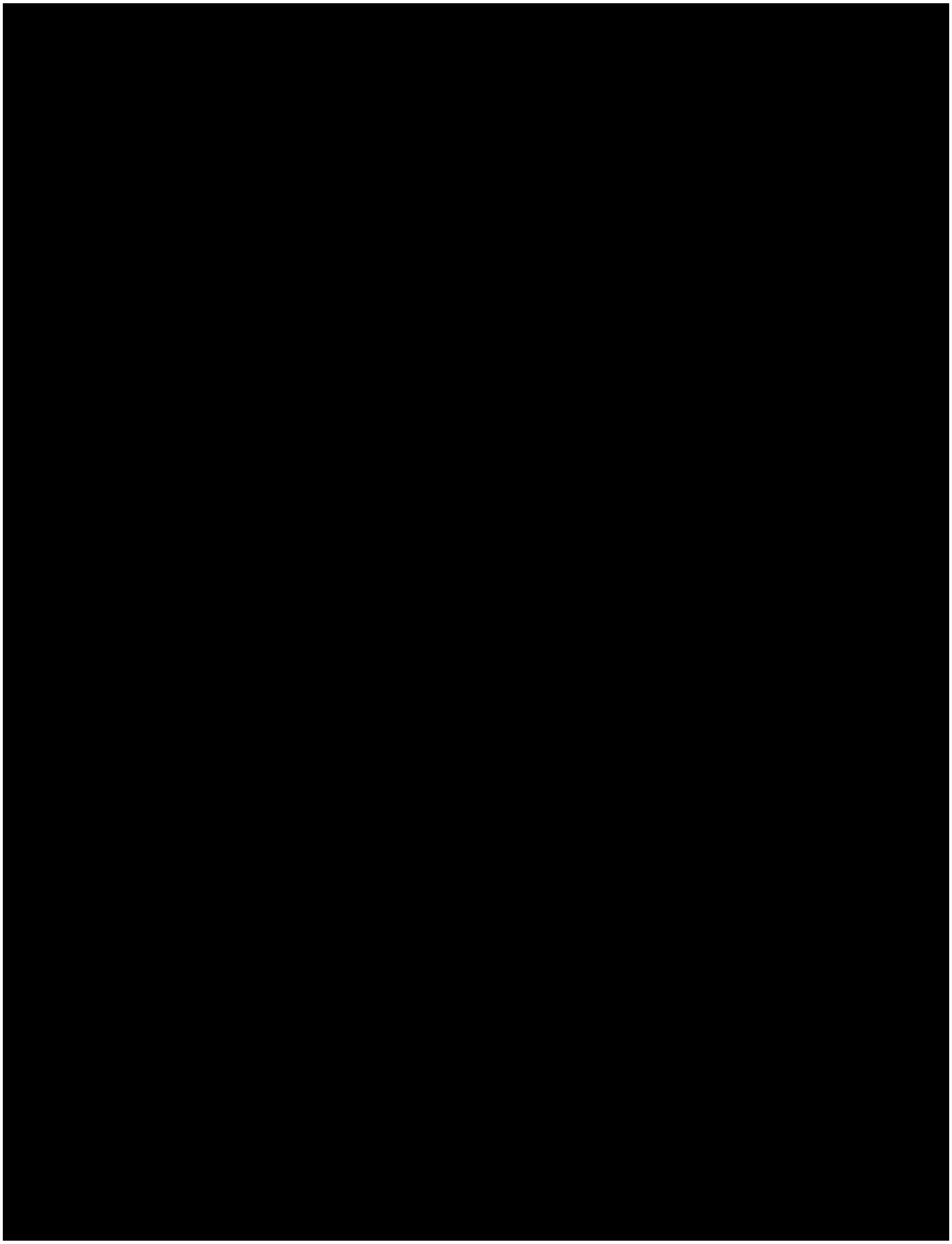

Figure I17. Swagelok pressure regulator (Sheet 1/2) [15]

[redacted]

Figure I18. Swagelok pressure regulator (Sheet 2/2) [15]

[redacted]

[redacted]

Figure I20. Swagelok high pressure relief device (Sheet 2/3) [16]

[redacted]

Figure I21. Swagelok high pressure relief device (Sheet 3/3) [16]

[redacted]

Figure I22. TE Connectivity low pressure transducer (Sheet 1/3) [17]

[redacted]

Figure I23. TE Connectivity low pressure transducer (Sheet 2/3) [17]

[redacted]

Figure I24. TE Connectivity low pressure transducer (Sheet 3/3) [17]

[redacted]

Figure I25. GC Valves low pressure solenoid valve (Sheet 1/2) [18]

[redacted]

Figure I26. GC Valves low pressure solenoid valve (Sheet 2/2) [18]

APPENDIX J: J4500E COACH POWER ANALYSIS

Appendix J details the calculations required to determine the J4500e coach power requirements.

APPENDIX J: LIST OF TABLES

The parameters of each duty cycle are detailed below:

10 Hour City Duty Cycle:

1) Accelerate to 48.3 km/h (30 mph).
2) Continuously drive at an average speed of 48.3 km/h for 1.6 km. Fully stop upon reaching 1.6 km.
3) Repeat steps one and two, twice.
4) Accelerate to 96.6 km/h (60mph).
5) Continuously drive at an average speed of 96.6 km/h for 4.8 km.

10 Hour Highway Duty Cycle:

1) Accelerate to 96.6 km/h.
2) Continuously drive at an average speed of 96.6 km/h for 10 hours.

Having identified the required duty cycles, the theoretical and experimental coach power analysis was conducted. The resulting power requirements from both modes of analysis were compared to determine the extent to which the experimentally derived power requirements meet their theoretical counterparts, for both city and highway conditions.

To theoretically calculate the J4500e coach power requirements, a tractive effort database is essential, containing physical, operational and environmental assumptions subjected to the coach. Information within this database is applied to theoretically calculate the J4500e coach power requirements. Table J1 shows the tractive effort database for the J4500e coach.

TABLE J1: TRACTIVE EFFORT PARAMETERS

Input Parameters	**Value**	**Units**	**Variable**	**Description**
Gross Vehicle Weight	24494	kg	m	All physical data pertains to the J4500e electric coach.
Frontal Area	9.35	m^2	A	
Drag Coefficient	0.4	-	C_D	The drag coefficient pertains to the J4500e coach. The rolling resistance coefficient assumes a road condition between good and wet asphalt road.
Rolling Resistance Coefficient	0.011	-	f	
Transmission Coefficient Efficiency	0.95	-	e	The transmission coefficient efficiency for the J4500e coach is 95%.
Force of Gravity	9.81	m/s^2	g	The force of gravity is constant.
Air Density	1.202	kg/m^3	ρ	The air density is constant.
Average Accessory Power	28	kW	L	The average accessory load for the J4500e coach is 28kW.
Average Speed, City Conditions	13.42	m/s	V_{city}	The average speed in city conditions.
Average Speed, Highway Conditions	26.83	m/s	V_{high}	The average speed in highway conditions.

The tractive effort parameters shown in Table J1 are applied to determine the rolling resistance and the aerodynamic drag, which combine to calculate the average power requirements of the J4500e coach, for both city and highway conditions. These derived parameters are defined in Table J2.

TABLE J2: DERIVED PARAMETERS FOR TRACTIVE EFFORT ANALYSIS

Parameter	**Units**	**Variable**
Aerodynamic Drag, City Conditions	N	D_{city}
Aerodynamic Drag, Highway Conditions	N	D_{high}
Rolling Resistance, City Conditions	N	R_{city}
Rolling Resistance, Highway Conditions	N	R_{high}
Average J4500e Coach Power Requirement, City Conditions (Theoretical)	kW	$P_{city,t}$
Average J4500e Coach Power Requirement, Highway Conditions (Theoretical)	kW	$P_{high,t}$

The aerodynamic drag and the rolling resistance, for city and highway conditions, are calculated as follows:

$$D_{city} = \frac{\rho C_d A {V_{city}}^2}{2} \quad \text{[J1]}$$

$$D_{high} = \frac{\rho C_d A {V_{high}}^2}{2} \quad \text{[J2]}$$

$$R_{city} = R_{high} = mgf \quad \text{[J3]}$$

Implementing the above equations, the average J4500e coach power requirement for city and highway conditions, developed theoretically, is as follows:

$$P_{city,t} = \frac{V_{city}}{e}\left(R_{city} + D_{city}\right) + L \quad \text{[J4]}$$

$$P_{high,t} = \frac{V_{high}}{e}\left(R_{high} + D_{high}\right) + L \quad \text{[J5]}$$

Employing a tractive analysis allows the J4500e coach power requirements to be calculated theoretically. Inputting the required parameters give:

$$P_{city,t} = 71.1\text{kW}$$

$$P_{high,t} = 148.1\text{kW}$$

To experimentally determine the J4500e coach power requirements, Motor Coach Industries, in conjunction with Siemens, conducted two road tests with the J4500e coach: one in city conditions and one in highway conditions. The experimental setup for both the city and highway conditions is identical to that of the duty cycles defined previously. Both road tests yielded the range efficiency which are summarized in Table J3.

TABLE J3: EXPERIMENTAL PARAMETERS

Input Parameters	**Value**	**Variable**
Range Efficiency City Condition (km/kWh)	0.66	ε_{city}
Range Efficiency Highway Condition (km/kWh)	0.68	ε_{high}

The range efficiency, in conjunction with the average speed, give the average J4500e coach power requirement. This derived average power, calculated experimentally, is defined as follows:

$$P_{city,e} = \frac{V_{city}}{\varepsilon_{city}} \quad [\text{ J6 }]$$

$$P_{high,e} = \frac{V_{high}}{\varepsilon_{high}} \quad [\text{ J7 }]$$

Employing an experimental analysis allows the J4500e coach power requirements to be calculated in a realistic atmosphere, thereby giving authentic power figures. Inputting the required parameters give:

$$P_{city,e} = 73.2\text{kW}$$

$$P_{high,e} = 142.1\text{kW}$$

The percent error between the experimentally and theoretically developed average J4500e coach power requirements is 3.0 and 4.1 for city and highway conditions, respectively. As the percent errors are minuscule, the experimental values coincide with their theoretical counterparts. This justifies the real-world data utilized to determine the coach power draw. Therefore, the coach power requirement selected for all subsequent analysis is determined experimentally. To further narrow the coach power requirement, the highest coach power draw, or the worst-case scenario, is selected from the experimentally derived values. This results in a final coach power draw of 142.1 kW, representative of the highway condition. Thus, 142.1 kW is the J4500e coach power requirement selected for all subsequent analysis.

APPENDIX K: FUEL CELL STACK EQUATIONS

Appendix K presents the equations used to quantify the evaluation criteria within the hydrogen fuel cell stack scoring and screening process.

Table K1 lists the relevant calculation parameters.

TABLE K1: FUEL CELL STACK CALCULATION PARAMETERS

Parameter	**Units**	**Variable**
Total Energy Required	kWh	E_{total}
Energy Supplied from Fuel Cell Stack	kWh	E_{FC}
Minimum Energy Required from Battery System	kWh	$E_{bat,min}$
Energy Required per Battery Pack	kWh	E'_{bat}
Mass of a Battery Pack	kg	m_{bat}
Mass of a Fuel Cell Stack	kg	m_{FC}
Combined Mass of Fuel Cell Stacks and Battery Packs	kg	m_{FC+bat}
Number of Battery Packs Required	-	N_{bat}
Minimum Number of Battery Packs Required	-	$N_{bat,min}$
Number of Fuel Cell Stacks	-	N_{FC}
Net Output Power Supplied from Fuel Cell Stack	kW	P_{FC}
Total Power Draw of Coach	kW	P_{total}
Required Driving Time	h	T_{drive}
Envelope of a Battery Pack	m^3	V_{bat}
Envelope of Fuel Cell Stack	m^3	V_{FC}
Combined Envelope of Fuel Cell Stacks and Battery Packs	m^3	V_{FC+bat}

The total amount of energy required is the product of the J4500e coach power draw and the drive time:

$$E_{total} = P_{total} \cdot T_{drive} \quad \text{[K1]}$$

The amount of energy supplied from the fuel cell stack is the product of the net output power of the fuel cell system and the drive time:

$$E_{FC} = P_{FC} \cdot T_{drive} \quad \text{[K2]}$$

The amount of energy required from the battery system is the difference between the total amount of energy required and the amount of energy supplied from the fuel cell stack:

$$E_{bat,min} = E_{total} - E_{FC} \quad \text{[K3]}$$

The minimum number of battery packs required is the quotient of the total amount of energy required from the battery system divided by the energy capacity of a single battery pack:

$$N_{bat,min} = \frac{E_{bat,min}}{E'_{bat}} \quad \text{[K4]}$$

The actual number of batteries required (N_{bat}) is determined by rounding up the minimum number of batteries required ($N_{bat,min}$) to the next largest integer.

The combined mass is calculated using the number and mass of fuel cell stacks, as well as the number and mass of battery packs:

$$m_{FC+bat} = N_{FC} \cdot m_{FC} + N_{bat} \cdot m_{bat} \quad \text{[K5]}$$

The combined envelope is calculated using the number and volume of fuel cell stacks, as well as the number and volume of battery packs

$$V_{FC+bat} = N_{FC} \cdot V_{FC} + N_{bat} \cdot V_{bat} \quad \text{[K6]}$$

APPENDIX L: FUEL CELL STACK SELECTION

Appendix L outlines the scoring and screening process for the hydrogen fuel cell stacks.

APPENDIX L: LIST OF TABLES

To select the optimal hydrogen fuel cell stack, a concept screening and a concept scoring was performed on the product lines from Ballard Power Systems. The hydrogen fuel cell stack concepts, developed from the stated product lines, are shown in Table L1.

TABLE L1: HYDROGEN FUEL CELL STACK CONCEPTS

Concept ID	**Hydrogen Fuel Cell Stack**
Ref.	HD100
A	HDV870
B	HD85
C	[redacted]

Concepts were selected to encompass a wide range of fuel cell stack performance capabilities, ensuring all possible options were considered. The selection criteria for the hydrogen fuel cell stack screening process are shown in Table L2, and are based on the established customer needs.

TABLE L2: SELECTION CRITERIA FOR FUEL CELL STACK

Selection Criteria	**Needs Addressed**	**Selection Definition**
Power Capacity	3, 4, 5, 7, 8, 9	This criterion refers to the power capacity of the fuel cell stack. A higher power capacity is desirable to reduce the number of batteries required.
Batteries Required	4, 5, 7, 8, 9, 10	This criterion refers to the amount of batteries needed to meet coach power requirements, given the power capacity of each fuel cell stack. The amount of batteries must be minimized to lessen the total mass and volume claim within the coach, whilst reducing cost.
Mass	1, 3, 6, 8	This criterion refers to the total mass of the fuel cell stack and the batteries needed to meet coach power requirements. The fuel cell stack, in conjunction with the batteries, must minimize mass to adhere to vehicle axle ratings.
Envelope	4, 5, 7, 8	This criterion refers to the maximum volume enveloped by the fuel cell stack and the batteries. A higher envelope reduces the space availability within the coach, thus the fuel cell stack, in conjunction with the batteries, must minimize the envelope.
Ease of Maintenance	1, 4, 8, 10	This criterion refers to the ease of maintenance for the fuel cell stack. The fuel cell must be easy to maintain.

The selection criteria portrayed in Table L2 are implemented in Table L3 to screen all presented concepts.

TABLE L3: HYDROGEN FUEL CELL STACK SCREENING PROCESS

	Fuel Cell Stack Concepts			
Selection Criteria	Ref.	A	B	C
Power Capacity	0	-	-	+
Batteries Required	0	-	-	+
Mass	0	-	-	+
Envelope	0	-	-	-
Ease of Maintenance	0	0	0	-
Net	0	-4	-4	1
Rank	2	3	3	1
Continue?	Y	N	N	Y

As shown in Table L3, the fuel cell stack concepts are screened with either a plus, neutral or minus rating, when compared to the reference. The net value of all ratings indicate the rank of each concept, with a higher rank corresponding to a better concept. The screening process is quantified in Table L4, using the equations listed in Appendix K. The table is color coded, with grey indicating a neutral assessment, green indicating a positive assessment and red indicating a negative assessment, when compared to the reference.

TABLE L4: HYDROGEN FUEL CELL STACK SCREENING JUSTIFICATION

Concepts	**Power Capacity (kW)**	**Batteries Required**	**Mass (kg)**	**Envelope (m^3)**	**Ease of Maintenance**
REF.	100	6	3510.6	0.85	Neutral (One Fuel Cell Stack)
A	70	10	5636.0	0.96	Neutral (One Fuel Cell Stack)
B	85	8	4556.8	0.92	Neutral (One Fuel Cell Stack)
C	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Referring to Table L3 and Table L4, the HD100 and the [redacted] fuel cell stacks are the strongest performers. These fuel cell stacks were further analyzed with a concept scoring process. Table L5 describes the weighing of all selection criteria within the scoring process.

TABLE L5: HYDROGEN FUEL CELL STACK SELECTION CRITERIA WEIGHING

	Criteria	A (Power Capacity)	B (Batteries Required)	C (Mass)	D (Envelope)	E (Ease of Maintenance)
Power Capacity	A		B	A	D	E
Batteries Required	B			C	D	B
Mass	C				C	C
Envelope	D					D
Ease of Maintenance	E					

	A	**B**	**C**	**D**	**E**
Total Hits	1	2	3	3	1
Weightings	0.10	0.20	0.30	0.30	0.10

As shown in Table L5, the mass and the envelope encompassing the fuel cell stack were weighted the most important, as it is crucial to minimize mass and adhere to space availability. These parameters were followed by the number of batteries required, the power capacity and the ease of maintenance. The weighted selection criteria are implemented in Table L6 to score the filtered hydrogen fuel cell stack concepts.

TABLE L6: HYDROGEN FUEL CELL STACK SCORING PROCESS

		Concepts			
		Ref.		C	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Power Capacity	0.10	2	0.2	4	0.4
Batteries Required	0.20	3	0.6	4	0.8
Mass	0.30	2	0.6	5	1.5
Envelope	0.30	4	1.2	3	0.9
Ease of Maintenance	0.10	4	0.4	2	0.2
Total Score		3.00		3.80	
Rank		2		1	
Develop?		N		Y	

With a total score of 3.80, the [redacted] fuel cell stack (Concept C) is ideal for the layout design. As shown in Table L2 and Table L4, [redacted] fuel cell stack is capable of supplying [redacted] of power at maximum operating conditions, reducing the amount of batteries required to a single pack, all whist meeting the J4500e coach power requirements. Additionally, both the mass and envelope are optimized at [redacted], respectively. Although the cost and the maintenance factor are mediocre, the positive performance of the [redacted] fuel cell stack vastly outweighs such discrepancies, creating a beneficial tradeoff and a hydrogen fuel cell stack that is ideal for the layout design.

APPENDIX M: EFFICIENCY EQUATIONS

Appendix M presents the equations used to determine the optimized number of battery packs and amount of hydrogen fuel required to achieve the design condition.

Table M1 lists the relevant calculation parameters.

TABLE M1: BATTERY AND HYDROGEN FUEL CAPACITY CALCULATIONS

Parameter	**Units**	**Variable**
Fuel Efficiency of Fuel Cell System	kWh/kg	ε_{fuel}
Energy Required from Battery System	kWh	E_{bat}
Energy Required per Battery Pack	kWh	E'_{bat}
Energy Supplied from Fuel Cell Stack	kWh	E_{FC}
Total Energy Required	kWh	E_{total}
Total Mass of Hydrogen Fuel Required	kg	$m_{fuel,req}$
Number of Battery Packs Required	-	N_{bat}
Net Output Power Supplied from Fuel Cell Stack	kW	P_{FC}
Required Driving Time	h	T_{drive}

The energy required from the battery system is the product of the number of battery packs and the energy per battery pack:

$$E_{bat} = N_{bat} \cdot E'_{bat} \quad \text{[M1]}$$

The energy supplied from the fuel cell stack is the difference between the total energy required and the energy required from the battery system:

$$E_{FC} = E_{total} - E_{bat} \quad \text{[M2]}$$

The net output power supplied from the fuel cell stack is the quotient of the energy supplied from the fuel cell stack and the drive time:

$$P_{FC} = \frac{E_{FC}}{T_{drive}} \qquad [M3]$$

The fuel efficiency of the fuel cell stack is a function of the net output power of the fuel cell stack.

$$\varepsilon_{fuel} = f(P_{FC}) \qquad [M4]$$

The fuel efficiency is found using Figure M1, with the calculated net output power.

Figure M1: HDV870 Fuel efficiency plot

The total mass of hydrogen fuel required is the quotient of the energy supplied from the fuel cell stack and the fuel efficiency:

$$m_{fuel,req} = \frac{E_{FC}}{\varepsilon_{fuel}} \qquad [M5]$$

APPENDIX N: HYDROGEN STORAGE TANK EQUATIONS

Appendix N contains the equations utilized to determine the scoring metrics for hydrogen storage tanks selection.

Scoring metrics for selection of the hydrogen storage thanks include determining the number of tanks required for a 10 hour highway haul at [redacted] fuel cell hydrogen consumption rate, determining the total mass of the hydrogen and hydrogen storage tanks, as well as the total envelope occupied by the tanks. The variables utilized throughout this analysis are presented in Table N1.

TABLE N1: VARIABLES USED IN HYDROGEN STORAGE TANK EQUATIONS

Parameter	**Units**	**Variable**
Total Mass of Hydrogen Fuel Required	kg	$m_{h_{2,total}}$
Hydrogen Capacity of a Hydrogen Storage Tank	kg	$m_{h_{2,tank}}$
Number of Tanks Required for the Storage of Total Mass of Hydrogen Fuel	-	N_{tank}
Mass of a Hydrogen Storage Tank	kg	$m_{mass,tank}$
Total Mass of all Hydrogen Storage Tanks and Hydrogen Fuel	kg	$m_{mass,total}$
Overall Length of a Hydrogen Storage Tank	m	L_{tank}
Overall Diameter of a Hydrogen Storage Tank	m	d_{tank}
Total Envelope Consumed by all the Hydrogen Storage Tank	m^3	$E_{tank,total}$

The first step in determining the total number of hydrogen storage tanks for a given tank is to determine the total amount of hydrogen fuel required. This is done by multiplying the total operation time 10 hours by the maximum hydrogen fuel cell consumption rate of [redacted] as shown in equation [N1] .

$$m_{h_{2,total}} = 10\ hour\ [redacted] \quad [\text{ N1 }]$$

The number of hydrogen storage tanks are then determined by dividing the total amount of hydrogen fuel required by the hydrogen capacity of the given tank, as shown in equation [N2].

$$N_{tank} = \frac{m_{h_{2,tank}}}{m_{h_{2,total}}} \quad [\text{ N2 }]$$

The total mass of the hydrogen storage tanks and the total hydrogen fuel is calculated by multiplying the mass of the given tank by the total number of hydrogen storage tanks, and adding the total hydrogen fuel mass to the product. This relationship is shown in equation [N3].

$$m_{mass,total} = (m_{mass,tank} \cdot N_{tank}) + m_{h_{2,total}} \quad [\text{ N3 }]$$

The total envelope consumed by all the hydrogen storage tanks is calculated by multiplying the volume of a storage tank by the total number of hydrogen storage tanks as shown in [N4]. The hydrogen storage tanks are assumed to be perfectly cylindrical in shape for simplification purposes.

$$E_{tank,total} = L_{tank}\left(\frac{\pi}{4} d_{tank}{}^{2}\right) \cdot N_{tank} \quad [\text{ N4 }]$$

APPENDIX O: HYDROGEN STORAGE TANK SELECTION

Appendix O outlines the scoring and screening process for the hydrogen storage tanks.

APPENDIX O: LIST OF TABLES

To select the optimal hydrogen storage tank, a concept screening and a concept scoring was performed on the product lines from Hexagon Composites. The hydrogen storage tanks were filtered to those which adhered to lateral space limitations within the frame of the J4500e coach (i.e. the length of the tanks must not exceed 2159 mm). These filtered tanks are shown in Table O1.

TABLE O1: HYDROGEN STORAGE TANKS CONCEPTS

Tank Model	**Nominal Working Pressure (MPa)**	**Length (mm)**
A	20	1060
I	70	906
J	70	1600
K	70	845
L	70	1050
[redacted]	[redacted]	[redacted]

The initial step in determining an optimal hydrogen tank was to select the selection criteria. The selection criteria for the hydrogen fuel cell stack screening process are shown in Table O2, on the established customer needs.

TABLE O2: SELECTION CRITERIA FOR HYDROGEN STORAGE TANKS

Selection Criteria	**Needs Addressed**	**Selection Definition**
Pressure Ratings	3, 7	This criterion refers to the fill pressure of the tanks. A higher pressure rating is desirable to increase storage capacity of the hydrogen fuel cell system.
Number of Tanks	3, 4, 5, 7, 8, 9	This criterion refers to the number of tanks required for a 10 hour highway haul at a fuel cell hydrogen consumption rate of 9.36 kg/h. The number of tanks must be reduced to reduce overall complexity of the hydrogen fuel cell system.
Mass	1, 3, 6, 9	This criterion refers to the total mass of hydrogen tanks and the hydrogen gas. This total mass must be reduced in order to reduce negative impacts to the desired range of the coach.
Envelope	4, 5, 7, 8	This criterion refers to the maximum volume enveloped by the hydrogen storage tanks. A higher envelope reduces the space availability within the coach, thus the hydrogen storage tanks must minimize the envelope.

The selection criteria shown in Table O2 was implemented in Table O3 to screen all presented concepts. Model J was chosen to be the reference concept, as it was the median of all the hydrogen tank concepts.

TABLE O3: HYDROGEN STORAGE TANK SCREENING PROCESS

	Hydrogen Storage Tank Concepts					
Selection Criteria	Ref.	A	I	K	L	M
Pressure Ratings	0	-	0	0	0	0
Number of Tanks	0	-	-	+	+	+
Mass	0	-	-	+	-	-
Envelope	0	-	+	+	+	+
Net	0	-4	-1	3	1	1
Rank	3	5	4	1	2	2
Continue?	N	N	N	Y	Y	Y

As shown in Table O3, the hydrogen storage tanks are screened with either a plus, neutral or minus rating, when compared to the reference. The net value of all ratings indicate the rank of each concept, with a higher rank corresponding to a better concept. The screening process is quantified in Table O4, using the equations listed in Appendix N. The table is color coded, with grey indicating a neutral assessment, green indicating a positive assessment and red indicating a negative assessment, when compared to the reference.

TABLE O4: HYDROGEN STORAGE TANKS SCREENING JUSTIFICATION

Tank Model	**Pressure Rating (MPa)**	**Number of Tanks**	**Mass (kg)**	**Envelope (m^3)**
Ref.	70	59	1804.6	4.2
A	20	134	2237.6	11.1
I	70	67	2371.6	4.9
K	70	36	1641.6	4.2
L	70	31	1922.6	4.9
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Referring to Table O3 and Table O4, hydrogen storage tanks Model K, L and M were the strongest performers. These hydrogen storage tanks were further analyzed with a concept scoring process. Table O5 describes the weighing of all selection criteria within the scoring process.

TABLE O5: HYDROGEN FUEL CELL STACK SELECTION CRITERIA WEIGHING

	Criteria	A (Pressure Rating)	B (Number of Tanks)	C (Mass)	D (Envelope)
Pressure Rating	A		A	C	D
Number of Tanks	B			B	B
Mass	C				D
Envelope	D				

	A	**B**	**C**	**D**
Total Hits	1	2	1	2
Weightings	0.17	0.33	0.17	0.33

The number of tanks and the total envelope of the hydrogen storage tanks were weighted the highest, with the pressure rating and mass following behind. The weighted selection criteria are implemented in Table O6 to score the filtered hydrogen fuel cell stack concepts, as shown.

TABLE O6: HYDROGEN STORAGE TANKS SCORING PROCESS

Concepts

		Model K		Model L		Model M	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Pressure Rating	0.17	5	0.85	5	0.85	5	0.85
Number of Tanks	0.33	2	0.66	3	0.99	5	1.65
Mass	0.17	5	0.85	3	0.51	3	0.51
Envelope	0.33	4	1.32	3	0.99	5	1.65
Total Score		3.68		3.34		4.66	
Rank		2		3		1	
Develop?		N		N		Y	

From the weighted decision matrix, Model M is the ideal hydrogen storage tank for this project's application. In order to satisfy the design requirements, only [redacted] Model M storage tanks are required which is the lowest amount of all tanks considered. Furthermore, these tanks occupy the lowest envelope [redacted] which is again the lowest of all the tanks considered. Although it ranks in the middle of the grouping regarding its mass, the number of tanks required and the total envelope the tanks occupy outweigh the mass considerations. Thus, an ideal hydrogen tank is selected using a systematic screening and scoring process.

APPENDIX P: FUEL CELL SYSTEM LAYOUT EQUATIONS

Appendix P presents the equations used to quantify the evaluation criteria within the fuel cell system layout scoring and screening process.

Table P1 lists the relevant calculation parameters used to determine the center of gravity of the major components within the hydrogen fuel cell system in relation to the battery electric system. The calculations use the front wall of compartment one as a common reference point.

TABLE P1: CENTER OF GRAVITY CALCULATION PARAMETERS

Parameter	**Units**	**Variable**
Center of Gravity of Hydrogen Fuel Cell System	m	CG_{system}
Center of Gravity of Battery-Electric System	m	CG_{old}
Center of Gravity of Battery-Electric System Relative to Hydrogen Fuel Cell System	m	CG_{rel}
Mass of Hydrogen Fuel Cell Battery Pack	kg	m_{bat}
Mass of Individual Battery Pack from Hydrogen Fuel Cell System	kg	$m_{bat,j}$
Mass of Individual Battery Pack for Battery-Electric System	kg	$m_{bat,old,j}$
Mass of Fuel Cell Stack	kg	m_{FC}
Mass of Individual Fuel Cell Stack	kg	$m_{FC,j}$
Hydrogen Capacity of the Fuel Cell System	kg	m_{h_2}
Hydrogen Capacity of an Individual Type of Storage Tank	kg	$m_{h_2,i}$
Hydrogen Capacity of an Individual Storage Tank	kg	$m_{h_2,j}$
Mass of the Hydrogen Fuel Cell System	kg	m_{system}
Mass of an Individual Type of Storage Tank	kg	$m_{tank,i}$
Mass of an Individual Storage Tank	kg	$m_{tank,j}$
Number of Battery Packs	-	N_{bat}
Number of Fuel Cell Stacks	-	N_{FC}
Number of Individual Types of Storage Tanks	-	$N_{tank,i}$
Distance of an Individual Battery Pack from Reference Point	m	$x_{bat,j}$
Distance of an Individual Fuel Cell Stack from Reference Point	m	$x_{FC,j}$
Distance of an Individual Storage Tank from Reference Point	m	$x_{tank,j}$

The hydrogen capacity of the fuel cell system is the summation of all the hydrogen fuel within each hydrogen storage tank:

$$m_{h_2} = \sum N_{tank,i} \cdot m_{h_2,i} \quad \text{[P1]}$$

The mass of the fuel cell system is the summation of the mass of the fuel cell stacks, the battery packs and the hydrogen storage tanks containing the hydrogen fuel:

$$m_{system} = N_{bat} \cdot m_{bat} + \sum N_{tank,i}(m_{tank,i} + m_{h_2,i}) + N_{FC} \cdot m_{FC} \quad \text{[P2]}$$

The center of gravity of the hydrogen fuel cell system is the summation of the moments for the fuel cell stacks, the battery packs and the hydrogen storage tanks containing the hydrogen fuel, divided by the mass of the fuel cell system:

$$CG_{system} = \frac{\sum(m_{bat,j} \cdot x_{bat,j}) + \sum[(m_{tank,j} + m_{h_2,j}) \cdot x_{tank,j}] + \sum(m_{FC,j} \cdot x_{FC,j})}{m_{system}} \quad \text{[P3]}$$

The center of gravity of the battery electric system is the summation of moments for the battery packs within the electric system divided by its mass:

$$CG_{old} = \frac{\sum m_{bat,old,j} \cdot x_{bat,old,j}}{\sum m_{bat,old,j}} \quad \text{[P4]}$$

The relative center of gravity is the difference between the center of gravity of the battery electric system and the hydrogen fuel cell system:

$$CG_{rel} = CG_{old} - CG_{system} \quad \text{[P5]}$$

APPENDIX Q: FUEL CELL SYSTEM LAYOUT SELECTION

Appendix Q outlines the scoring and screening process for the fuel cell system layout of all core components.

APPENDIX Q: LIST OF FIGURES

APPENDIX Q: LIST OF TABLES

To select the optimal fuel cell system layout, a concept screening and a concept scoring was performed on four layout concepts, containing the major components, as well as the BMS, the BTMS, the FCTMS and the electric heater configured into varying arrangements. The final specifications for the major components are summarized in Table Q1. For all the concepts, seven Model M hydrogen storage tanks were chosen as it maximized the hydrogen storage within the available space of the J4500e coach while leaving some unoccupied space for the placement of auxiliary components. The performance of the listed components give a total hydrogen capacity of [redacted] and a maximum range of 7 hours at 60 mph for the J4500e coach.

TABLE Q1: MAJOR COMPONENT SUMMARY

Component	**Model**	**Quantity**
Fuel Cell Stack	[redacted]	2
Battery Pack	XMP76P	1 (7 modules)
Storage Tank	Model M	7

In order to distinguish all components within the fuel cell system, the layout concepts are color coded according to Table Q2.

TABLE Q2: COLOUR CODE FOR FUEL CELL SYSTEM LAYOUTS

Color	**Component**
Grey	J4500e Coach Frame
Light Blue	[redacted] Fuel Cell Stacks
Orange	XMP76P Battery Pack
Navy Blue	Model M Tank
Green	BTMS and FCTMS
Purple	BMS
Red	Electric Heater

Having fully defined the design space of all layout concepts, each fuel cell system layout is elucidated as follows.

Fuel Cell System Layout A

Fuel Cell System Layout A is presented in Figure Q1. All components are labelled in this figure for further clarification.

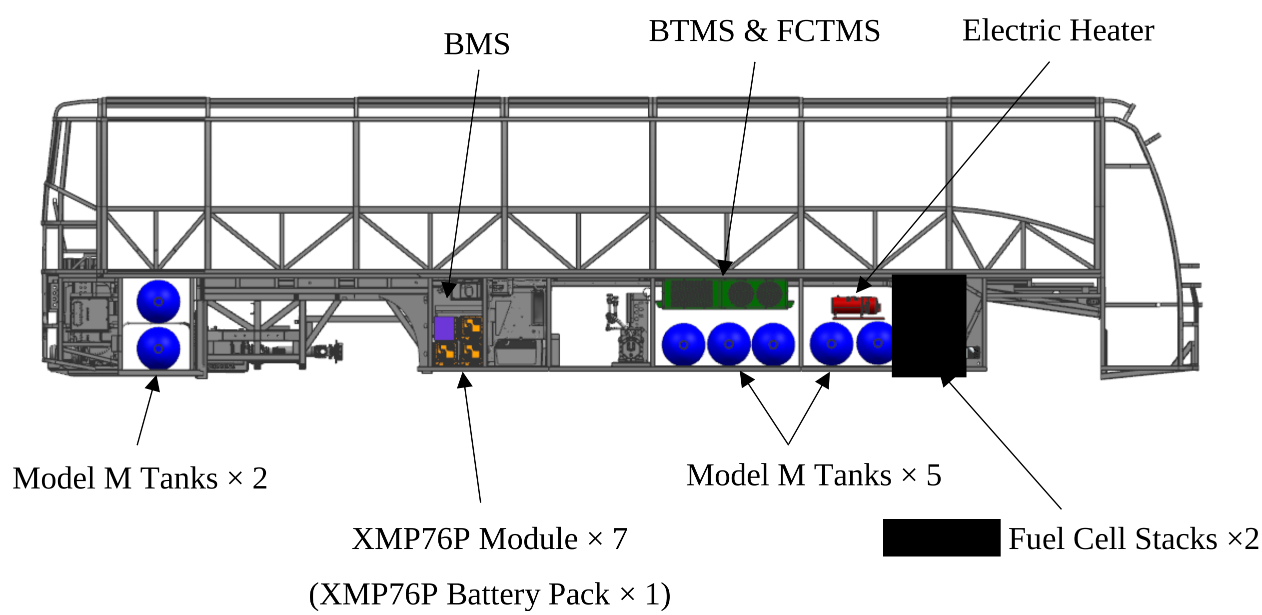

Figure Q1. Fuel Cell System Layout A passenger side view

Fuel Cell System Layout A from the driver side is shown in Figure Q2.

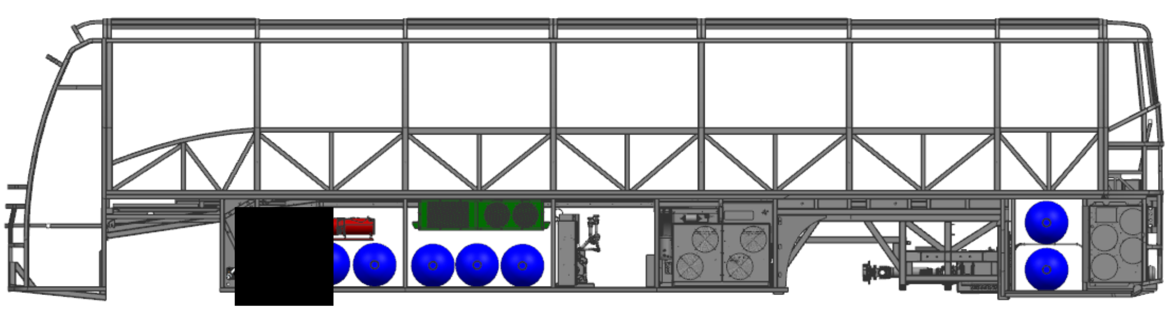

Figure Q2. Fuel Cell System Layout A driver side view

The top views of each compartment for Fuel Cell System Layout A are shown in Figure Q3 to Figure Q6. Compartment three is unoccupied to be used as a baggage compartment.

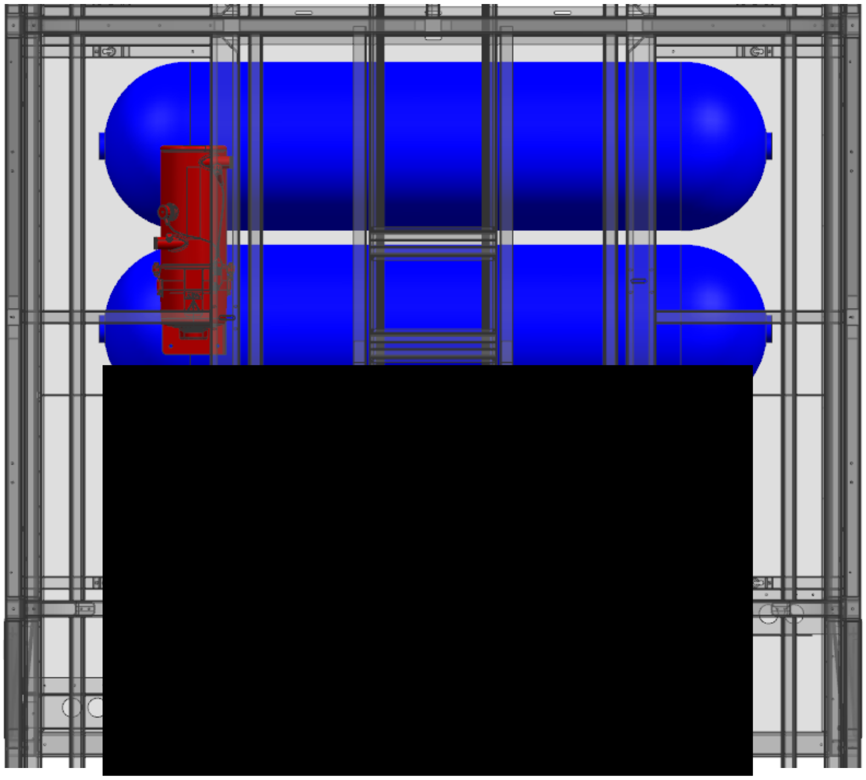

Figure Q3. Fuel Cell System Layout A compartment one

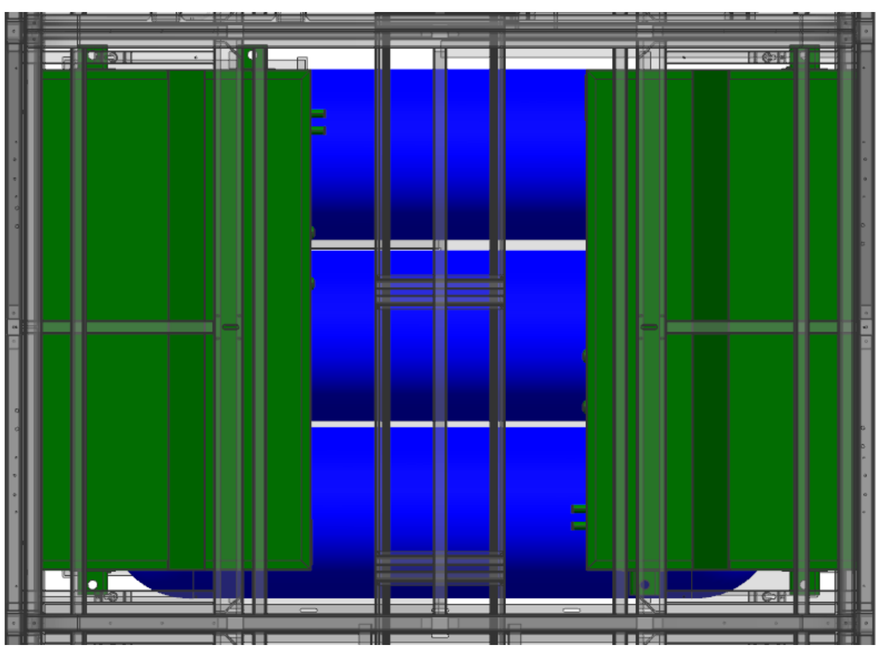

Figure Q4. Fuel Cell System Layout A compartment two

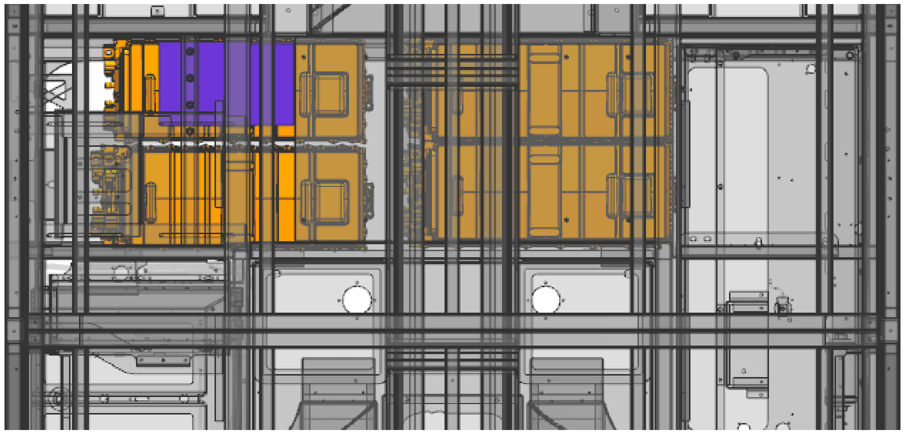

Figure Q5. Fuel Cell System Layout A compartment four

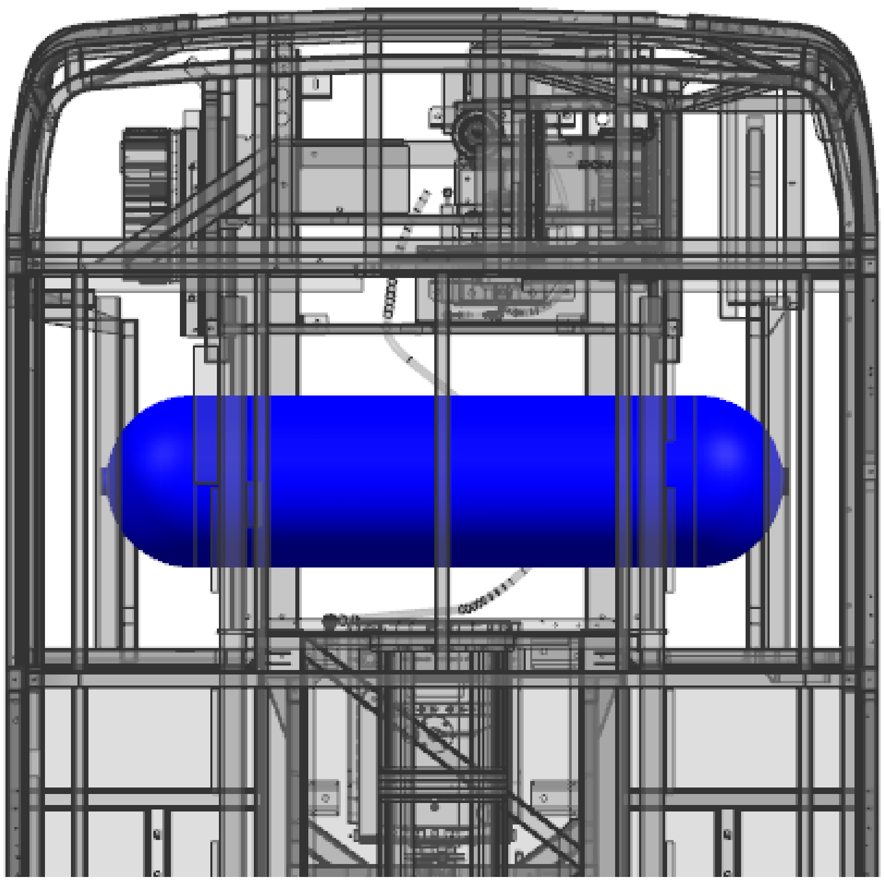

Figure Q6. Fuel Cell System Layout A compartment five

In Fuel Cell System Layout A, compartment one contains the fuel cell stacks, positioned vertically, and two Model M tanks, placed laterally. Compartment two contains the BTMS and the FCTMS, placed on the same plane, with the fans facing either side of the coach. Three Model M tanks are placed beneath. Compartment four contains the battery pack and the BMS and compartment five contains two Model M tanks.

This layout has the advantage of utilizing some of the existing structure in compartment two, in order to attach the FCTMS and the BTMS. However, slight modifications are required to accommodate the three Model M tanks in compartment two. Within the battery electric coach, compartment two housed the battery packs which are removed in Fuel Cell System Layout A. Thus, compartment two requires modifications as illustrated in Figure Q7.

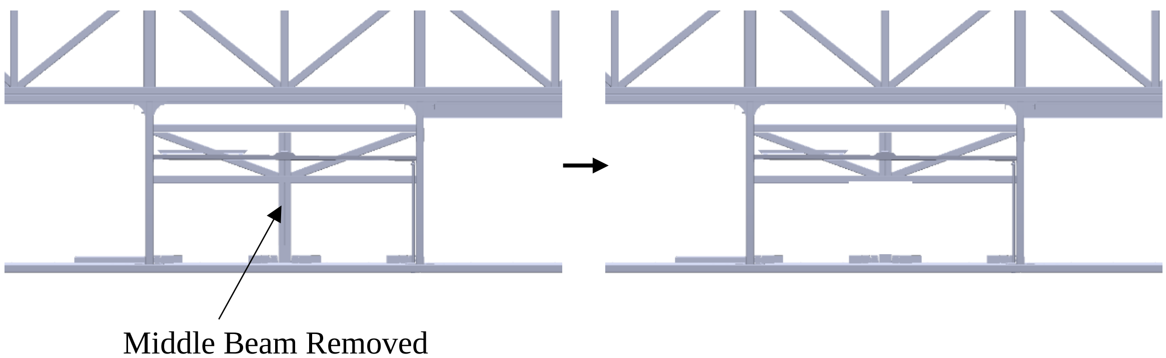

Figure Q7: Beam removal and platform addition within compartment two structures

Fuel Cell System Layout B

Fuel Cell System Layout B is presented in Figure Q8 and Figure Q9.

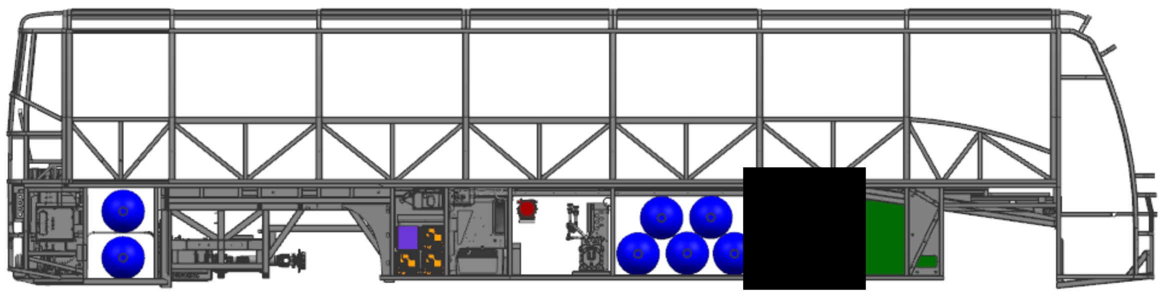

Figure Q8: Fuel Cell System Layout B passenger side view

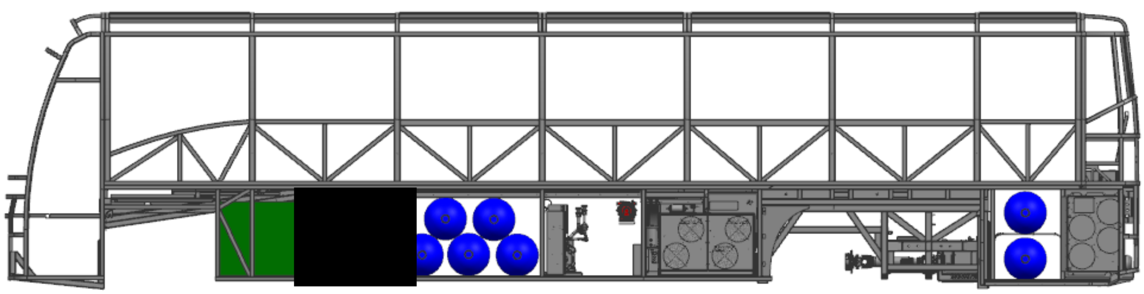

Figure Q9. Fuel Cell System Layout B driver side view

The top views of each compartment for Fuel Cell System Layout B are shown in Figure Q10 to Figure Q14.

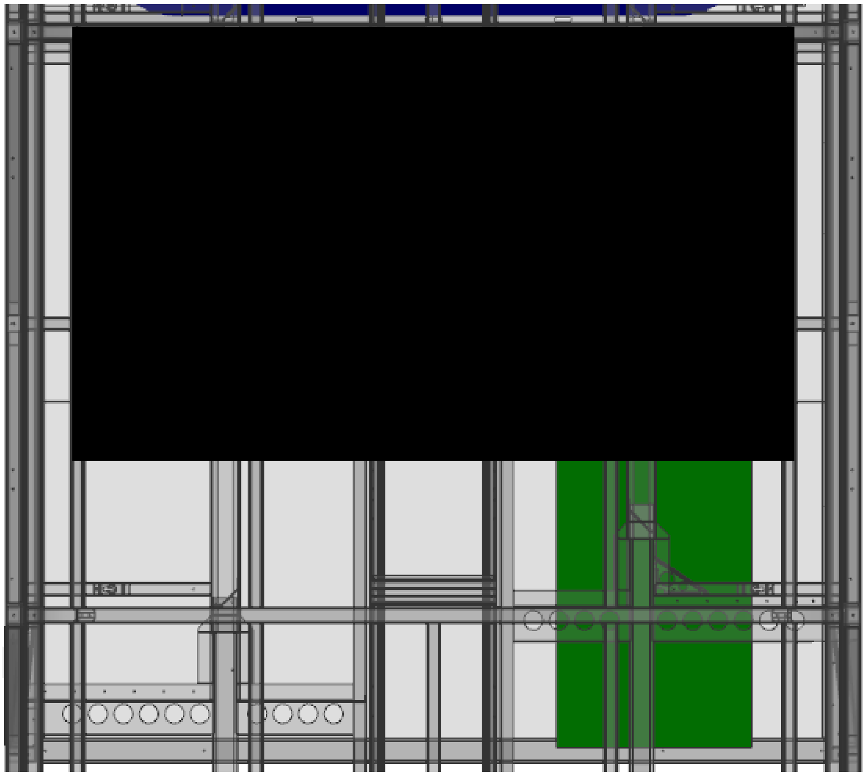

Figure Q10. Fuel Cell System Layout B compartment one

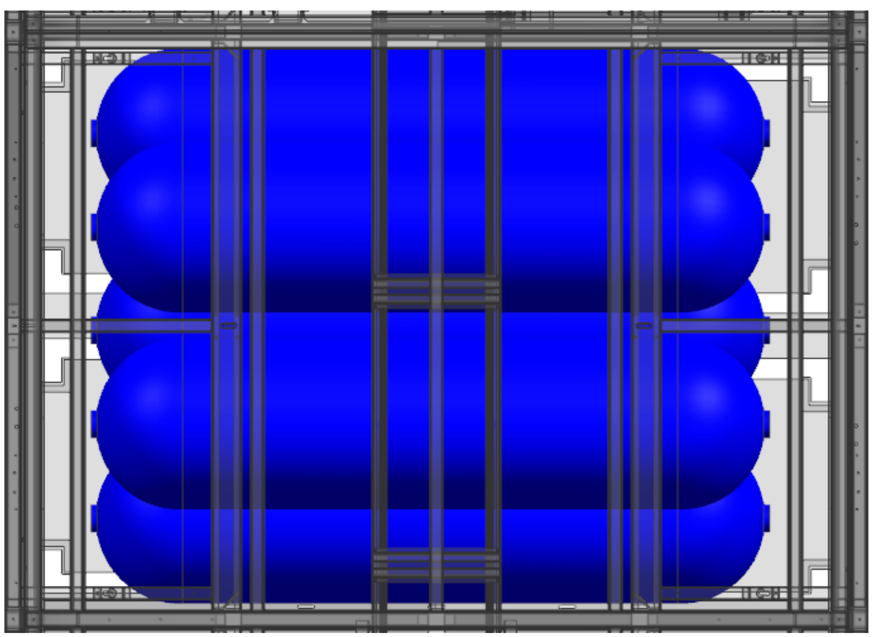

Figure Q11. Fuel Cell System Layout B compartment two

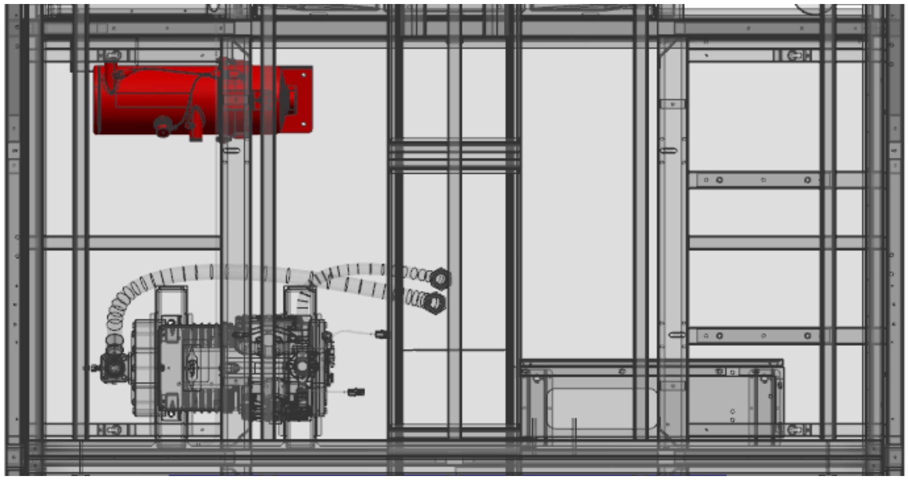

Figure Q12. Fuel Cell System Layout B compartment three

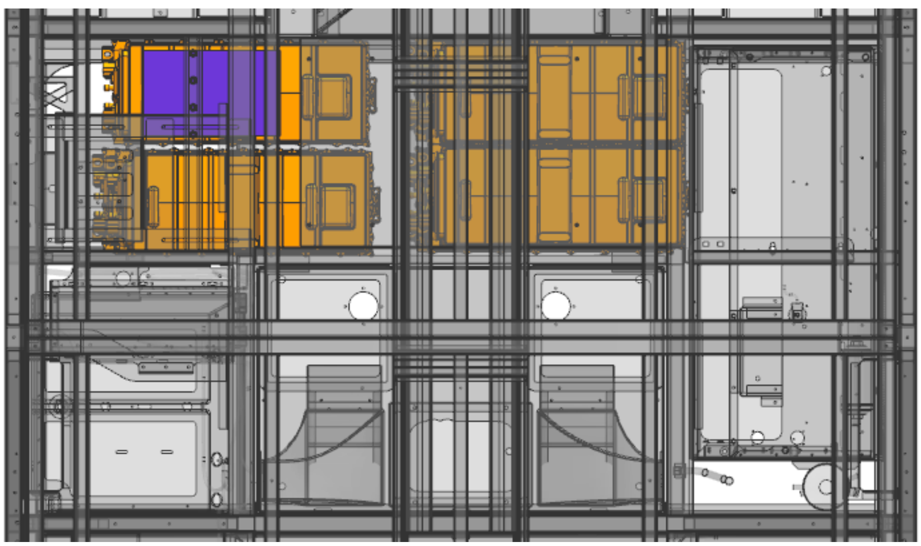

Figure Q13. Fuel Cell System Layout B compartment four

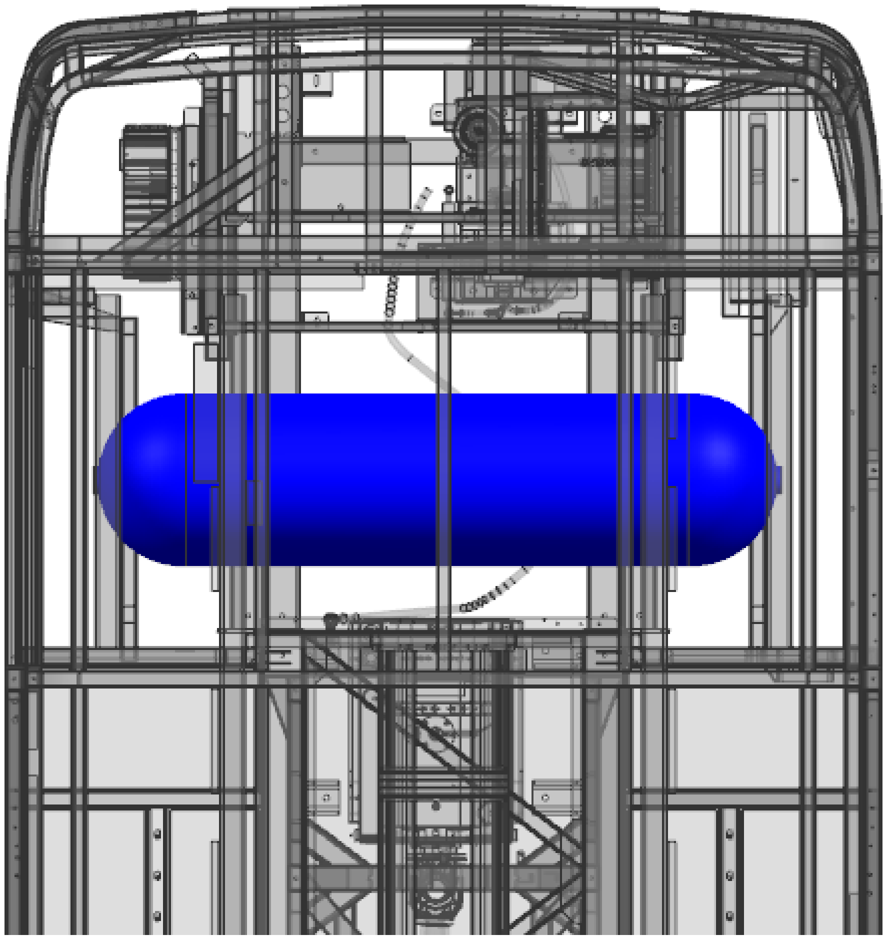

Figure Q14. Fuel Cell System Layout B compartment five

In Fuel Cell System Layout B, compartment one contains the fuel cell stacks positioned vertically, and the BTMS and the FCTMS combined into one unit. Compartment two contains five Model M tanks, placed in a pyramidal shape and compartment three contains the electric heater, with its space claim minimized to allow compartment three to be utilized as a baggage bay. Compartment four contains the battery pack, alongside the BMS and compartment five contains the remaining two Model M tanks placed vertically.

This layout has the advantage of grouping the tanks into compartment two and five, making the maintenance of all tanks easier. However, the tanks in compartment two are restricted in terms of the available space, creating installation difficulty. In addition, the entire structure within compartment two requires removal as shown in Figure Q15.

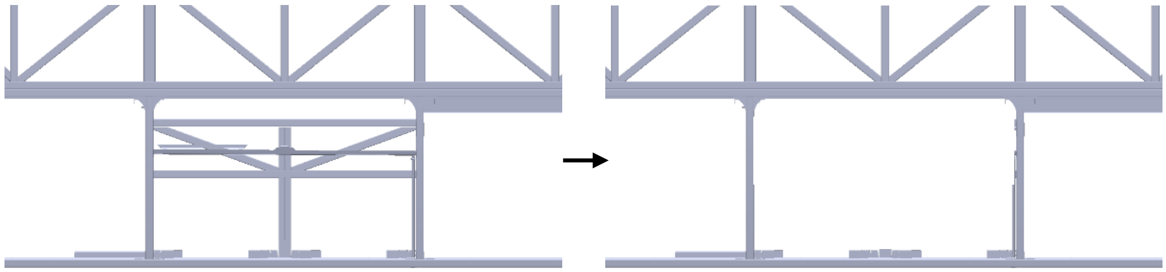

Figure Q15: Removal of compartment two structures

Fuel Cell System Layout C

Fuel Cell System Layout C is presented in Figure Q16 and Figure Q17.

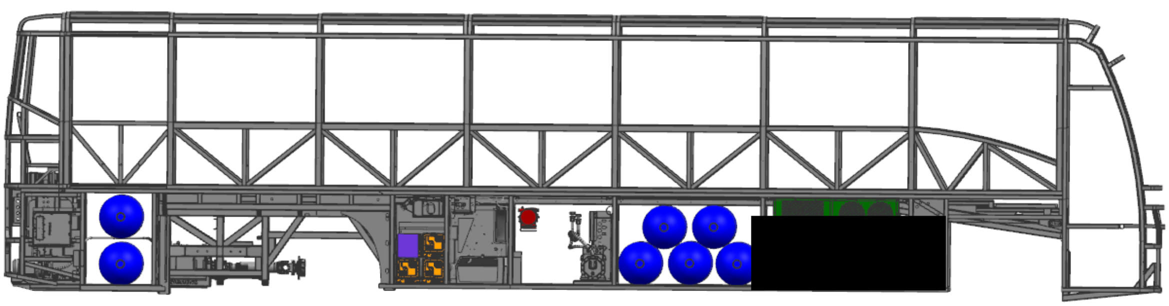

Figure Q16: Fuel Cell System Layout C passenger side view

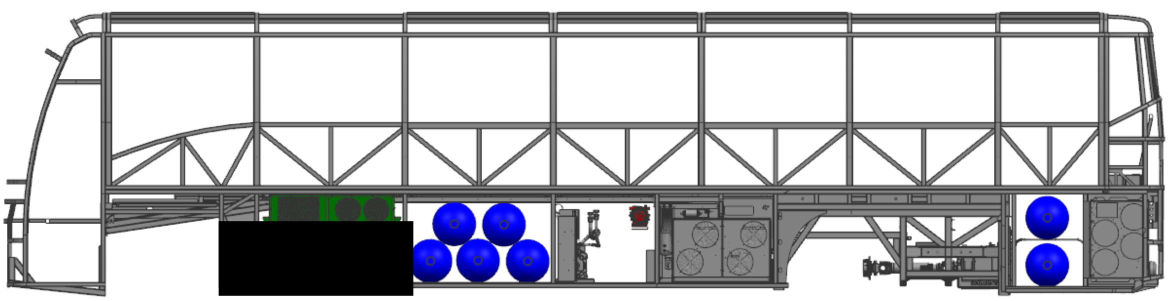

Figure Q17. Fuel Cell System Layout C driver side view

Fuel Cell System Layout C is identical to that of Fuel Cell System Layout B for compartments two, three, four and five. The only change is in compartment one as shown in Figure Q18.

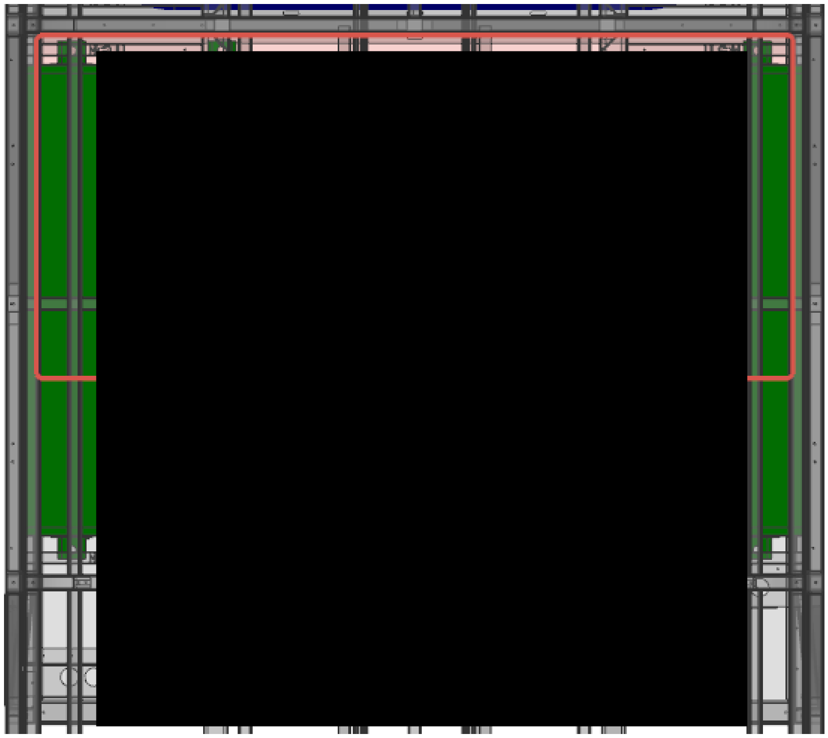

Figure Q18. Fuel Cell System Layout C compartment one

In Fuel Cell System Layout C, compartment one contains the fuel cell stacks, positioned horizontally across the base of the coach, while the BTMS and the FCTMS are placed on either side of the coach on top of the fuel cell stacks. This configuration reduces the installation complexity of the fuel cell stacks. However, similar to Fuel Cell System Layout B, the tanks in compartment two are restricted in terms of the available space, creating installation difficulty and the entire structure within compartment two requires removal as shown in Figure Q15.

__Fuel Cell System Layout D__

Fuel Cell System Layout D is presented in Figure Q19 and Figure Q20.

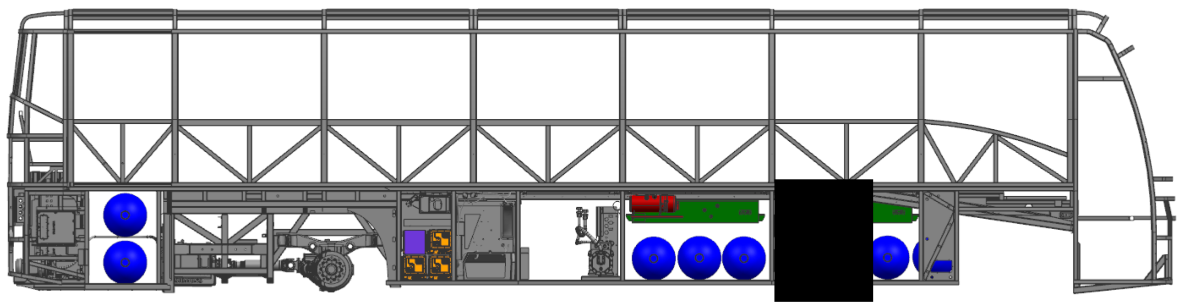

Figure Q19: Fuel Cell System Layout D passenger side view

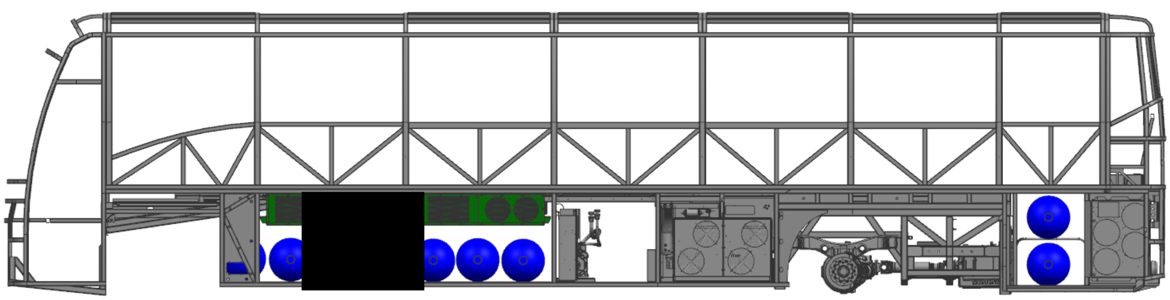

Figure Q20. Fuel Cell System Layout D driver side view

This layout is similar to layout A, except that the BTMS and FCTMS are placed in compartment two and one respectively and face the driver's side of the coach. Fuel Cell System Layout D is identical to that of Fuel Cell System Layout B and C for compartments three, four and five. The changes in compartment one and two are shown in detail

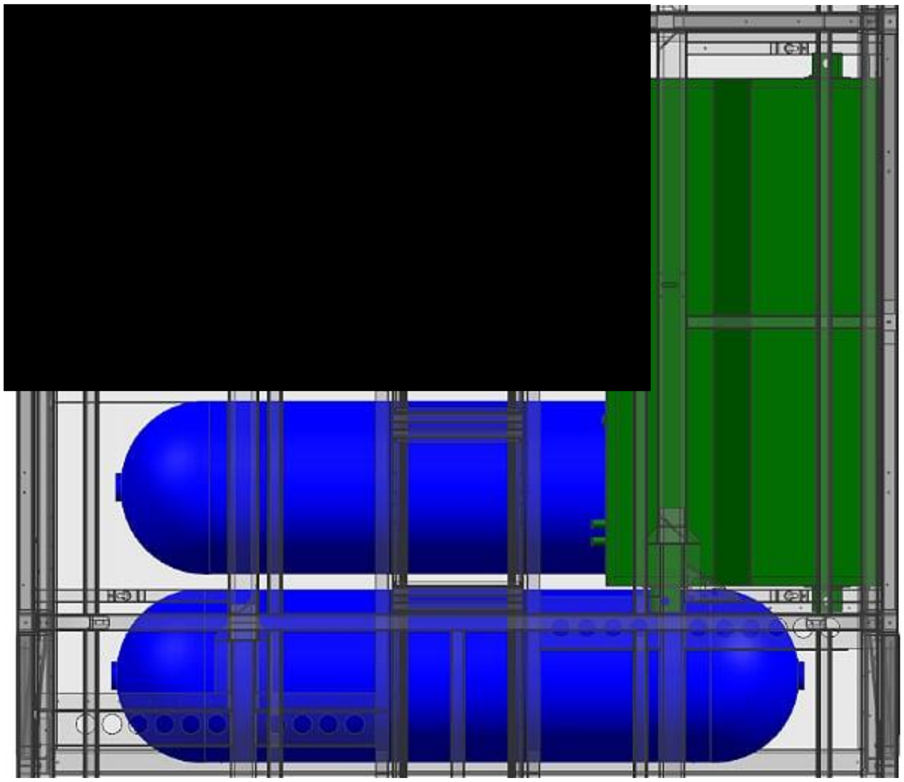

Figure Q21. Fuel Cell System Layout D compartment one

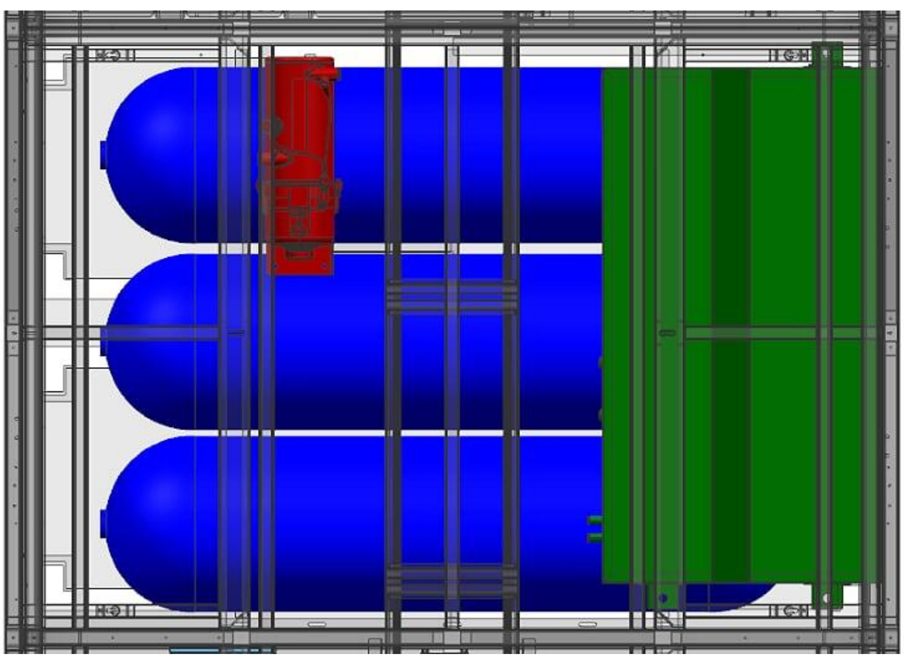

Figure Q22. Fuel Cell System Layout D compartment two

Like layout A, this layout has advantage of using the some of the existing structure in compartment two to attach BTMS and the electric heater to. In other words, the BTMS and the electric heater can stay in the same location and use the same structure as in MCI's electric coach which reduces future workload. However, the same modifications that were needed to accommodate the three Model M tanks in layout A will need to be made here as well. The modifications required are shown in Figure Q7.

With all the concepts defined, the selection criteria for the fuel cell system layout screening process are shown in Table Q3, and are based on the customer needs shown in Table Q3.

TABLE Q3: SELECTION CRITERIA FOR FUEL CELL SYSTEM LAYOUT

Selection Criteria	**Needs Addressed**	**Selection Definition**
Structure Re-design	6, 9	This criterion refers to the amount of re-design required to the existing coach frame to integrate the hydrogen fuel cell system. The amount of structure re-design must be limited to a minimum in order to reduce costs of implementing the system.
Safety	1, 2, 3	This criterion refers to the overall safety of the hydrogen fuel cell system design, for both passengers in and around the coach.
Relative CG	1, 8	This criterion refers to the relative distance of the CG of the hydrogen coach to that of the electric coach. The distance between the CG of the electric coach with the corresponding batteries must stay relatively close to the new layout with the corresponding batteries. This is to minimize mass effects on the existing axle loads and stay within the axle load requirements.

Complexity	5, 6, 9, 11	This criterion refers to the complexity of installation of the hydrogen fuel cell system layout design. The system must be able to be easily implemented into the current coach. Appropriate distances must be maintained between components to allow for tolerances and future expansion work.

The selection criteria shown in Table Q3 are implemented in Table Q4 to screen all presented concepts. Fuel Cell System Layout A was chosen as the reference case.

TABLE Q4: HYDROGEN FUEL CELL SYSTEM LAYOUT SCREENING PROCESS

	Hydrogen Fuel Cell Layout Concepts			
Selection Criteria	Ref. (A)	B	C	D
Structure Re-design	0	-	-	0
Safety	0	-	-	+
Relative CG	0	+	+	+
Complexity	0	-	-	0
Net	0	-2	-2	2
Rank	2	3	3	1
Continue?	Y	N	N	Y

As shown in Table Q4 , the fuel cell systems are screened with either a plus, neutral or minus rating, when compared to the reference. The net value of all ratings indicate the rank of each concept, with a higher rank corresponding to a better concept. The screening process is quantified in Table Q5, using the equations listed in Appendix P for the center of gravity of each layout. The table is color coded, with grey indicating a neutral assessment, green indicating a positive assessment and red indicating a negative assessment, when compared to the reference.

TABLE Q5: RELATIVE CG OF EACH FUEL CELL SYSTEM LAYOUT

Layout Concept	**Relative CG (m)**
Ref. (A)	2.32 (front)
B	1.80 (front)
C	1.94 (front)
D	2.14 (front)

Referring to Table Q4 and Table Q5, Fuel Cell System Layout A (the reference) and Fuel Cell System Layout B are the strongest performers. These fuel cell system layouts were further analyzed with a concept scoring process. Table Q6 describes the weighing of all selection criteria within the scoring process.

TABLE Q6: HYDROGEN FUEL CELL SYSTEM LAYOUT SELECTION CRITERIA WEIGHING

		Structure Re-design	Safety	Relative CG	Complexity
	Criteria	A	B	C	D
Structure Re-design	A		B	C	A
Safety	B			B	B
Relative CG	C				D
Complexity	D				

	A	**B**	**C**	**D**
Total Hits	1	3	1	1
Weightings	0.17	0.50	0.16	0.17

As shown in Table Q6, the safety of the fuel cell system layout was weighted the most important as it is a crucial need. This parameter was followed by the structural re-design of the J4500e electric coach, the complexity of the fuel cell system layout and the relative center of gravity. The weighted selection criteria are implemented in Table Q7 to score the fuel cell system layouts.

TABLE Q7: WEIGHTED DECISION MATRIX FOR HYDROGEN FUEL CELL LAYOUT DESIGN

		Ref. (A)		**D**	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Structure Re-design	0.17	3	0.51	3	0.51
Safety	0.50	3	1.5	5	2.5
Relative CG	0.16	2	0.32	3	0.48
Complexity	0.17	2	0.34	3	0.51
Total Score		2.67		4	
Rank		2		1	

Based on the weighted decision matrix, Fuel Cell System Layout D was the ideal layout. With seven Model M hydrogen storage tanks, this layout provides a maximum range of 7 hours at 60 mph. This layout requires the least structural re-design as only one member in compartment two needs to be removed. The existing structure is capable of allowing installation of the fuel cell stacks, the battery packs, the BMS, the BTMS, the FCTMS and the electric heater. As an added safety measure, the BTMS and the FCTMS face the driver's side, preventing any radiator intake or exhaust from interacting with embarking or disembarking passengers. There is no stacking of hydrogen storage tanks, which reduces the complexity of the layout and increases the safety of coach operation. T

APPENDIX R: AIR INTAKE AND EXHAUST PRESSURE DROP CALCULATIONS

This appendix presents the calculations used to determine the amount of pressure drop in the air intake and amount of backpressure in the exhaust of the fuel cell.

TABLE I: INTAKE AND EXHAUST PRESSURE DROP CALCULATION PARAMETERS

Parameter	**Units**	**Variable**
Pipe Area	m^2	A
Pipe Diameter	m	D
Absolute Roughness	m	ε
Darcy–Weisbach Friction Factor	-	f
Total Pipe Length	m	L
Mass Flow Rate	kg/s	$\dot{m}$
Minor Loss Coefficient	-	ξ_i
Dynamic Viscosity	$N \cdot s/m^2$	μ
Total Pressure Loss	mbar	P_{loss}
Major Pressure Loss	mbar	$P_{loss,major}$
Minor Pressure Loss	mbar	$P_{loss,minor}$
Density	kg/m^3	ρ
Reynold's Number	-	Re_D
Mean Flow Velocity	m/s	V

$$A = \pi \cdot \frac{D^2}{4} \quad \text{[R1]}$$

$$V = \frac{\dot{m}}{\rho A} \quad \text{[R2]}$$

$$Re_D = \frac{\rho V D}{\mu} \quad \text{[R3]}$$

$$f = \left[-1.8 \log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]\right]^{-2}$$ [R4]

$$P_{loss,major} = f\,\frac{L}{D}\frac{\rho V^2}{2} * \frac{1\ mbar}{100\ Pa}$$ [R5]

$$P_{loss,minor} = \sum_{i=1}^{n} \xi_i\,\rho\,\frac{V^2}{2} * \frac{1\ mbar}{100\ Pa}$$ [R6]

$$P_{loss} = P_{loss,major} + P_{loss,minor}$$ [R7]

APPENDIX S: HYDROGEN LINE PRESSURE DROP CALCULATIONS

This appendix presents the calculations used to determine the amount of pressure drop in most restrictive hydrogen piping run.

Parameter	**Units**	**Variable**
Pipe Area	m^2	A
Pipe Diameter	m	D
Absolute Roughness	m	ε
Darcy–Weisbach Friction Factor	-	f
Total Pipe Length	m	L
Equivalent Friction Loss Length	m	L_e
Mass Flow Rate Per Run of Pipe	kg/s	$\dot{m}$
Total Mass Flow Rate	kg/s	$\dot{m}_{total}$
Minor Loss Coefficient	-	ξ_i
Dynamic Viscosity	$N \cdot s/m^2$	μ
Total Pressure Loss	Pa	P_{loss}
Major Pressure Loss	Pa	$P_{loss,major}$
Minor Pressure Loss	Pa	$P_{loss,minor}$
Density	kg/m^3	ρ
Reynold's Number	-	Re_D
Mean Flow Velocity	m/s	V

[S1]

$$\dot{m} = \frac{\dot{m}_{total}}{N_{runs}}$$

$$A = \pi \cdot \frac{D^2}{4} \quad [S2]$$

$$V = \frac{\dot{m}}{\rho A} \quad [S3]$$

$$Re_D = \frac{\rho V D}{\mu} \quad [S4]$$

$$f = \left[-1.8 \log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]\right]^{-2} \quad [S5]$$

$$P_{loss,major} = f\frac{L}{D}\frac{\rho V^2}{2} \quad [S6]$$

$$P_{loss,minor} = f N_{bends}\frac{L_e}{D}\frac{\rho V^2}{2} \quad [S7]$$

$$P_{loss} = P_{loss,major} + P_{loss,minor} \quad [S8]$$

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