CALIFORNIA ENERGY COMMISSION

California Energy Commission
Clean Transportation Program

FINAL PROJECT REPORT

Hydrogenics Advanced Fuel Cell Vehicle Technology Demonstration for Transit Bus

Prepared for: California Energy Commission

Prepared by: Cummins Electrified Power NA Inc.

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-14-605 to share the cost of the field demonstration of truck technologies that may become commercially available in California. In response to PON-14-605, the recipient submitted an application that was proposed for funding in the CEC's notice of proposed awards June 18, 2015, and the agreement was executed as ARV-15-001 on August 1, 2015.

ABSTRACT

This final report documents the design, building, integration, testing, and demonstration of Hydrogenics USA, Inc.'s advanced hydrogen fuel cell propulsion system for heavy-duty vehicles under the California Energy Commission Agreement Number ARV-15-001. This project sought to demonstrate the technical and commercial viability of an advanced hydrogen fuel cell propulsion system that would lead to market adoption and product commercialization.

Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology purposely designed and developed for transit buses. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a transit bus. Funding from the California Energy Commission was critical to the overall success of Hydrogenics Corporation. By selecting Hydrogenics, the California Energy Commission's grant review process provided a valuable third-party evaluation of its business model for Cummins Inc.'s due diligence before its acquisition of the company in 2019.

The Hydrogenics Advanced Fuel Cell Bus successfully operated on several transit bus routes, including SunLine Transit Agency's most challenging route. The Hydrogenics Advanced Fuel Cell Bus represents a meaningful step in the hydrogen fuel cell industry. For Cummins, it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Keywords: Cummins Inc., Cummins, Cummins New Power, Hydrogenics Corporation, Hydrogenics USA, Inc., Hydrogenics, hydrogen, fuel cell, fuel cell electric vehicle

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EXECUTIVE SUMMARY

To demonstrate advanced truck and bus technologies that may become commercially available in California, Hydrogenics USA, Inc. proposed to the California Energy Commission (CEC) to demonstrate the technical and market viability of an advanced zero-emission hydrogen fuel cell propulsion technology designed and developed for medium- and heavy-duty mobility applications. This proposed advanced propulsion technology was to expedite commercialization of hydrogen fuel cell medium and heavy-duty commercial vehicles by significantly reducing development, integration, and production cost of building fuel cell hybrid vehicles. The requested CEC funding was to be matched by Hydrogenics USA, Inc.'s and New Flyer Industries' funding to integrate the proposed advanced fuel cell propulsion technology into a transit bus and demonstrate it in real-world transit operation.

The project was kicked off in August 2015 but faced a series of challenges typical in the earlier phase of the fuel cell industry. Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology designed and developed for transit buses. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a transit bus. Funding from the CEC was critical to the overall success of Hydrogenics Corporation. By selecting Hydrogenics, the CEC's grant review process provided a valuable third-party evaluation of its business model for Cummins' due diligence before its acquisition of the company in 2019. The Hydrogenics Advanced Fuel Cell Bus successfully operated on several transit bus routes, including SunLine Transit Agency's most challenging route. The Hydrogenics Advanced Fuel Cell Bus represents a meaningful step in the hydrogen fuel cell industry. For Cummins, it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Going forward, Cummins is involved in several projects pursuing its most up-to-date heavy-duty fuel cell powertrain architecture and design. It incorporates the key learnings from this project and leapfrogs incremental design improvements on a powertrain architecture and design originally developed in 2015. Cummins' latest generation architecture and design bring forward a state-of-the-art fuel cell powertrain that 1) is customized, tested, and optimized for transit bus applications; 2) can demonstrate the market viability of advanced zero-emission fuel cell drive system technology in a transit bus; and 3) accelerates the mass market penetration of heavy-duty hydrogen fuel cell buses.

CHAPTER 1: Project Overview

Hydrogenics USA, Inc.

Hydrogenics Corporation (Hydrogenics) was founded in 1995 as a developer and manufacturer of hydrogen generation and fuel cell products based on water electrolysis and proton exchange membrane technology. Hydrogenics quickly grew as a market leader for the design and manufacture of industrial and commercial fuel cell and hydrogen production technologies, having supplied more than 2,000 fuel cells and realized more than 600 electrolyzer installations in 100 countries (Figure 1). Hydrogenics USA, Inc. (Hydrogenics USA) in Carlsbad (San Diego County) was Hydrogenics' production plant and sales office in California.

Figure 1: Hydrogenics' Fuel Cell Manufacturing Line (left) and Electrolyzer Installation in Bécancour, Canada (right)

Source: Cummins Inc.

In September 2019, Cummins Inc. (Cummins) closed on its acquisition of Hydrogenics Corporation, another step forward as Cummins continues to invest in a broad range of clean, fuel-efficient, and high-performing products and technologies that deliver value to its customers. Hydrogenics provides Cummins with a unique collection of intellectual property and technology for its fuel cell portfolio, a proven team, and a long track record of commercial success in a technology that is beginning to accelerate. The acquisition accelerates Cummins' ability to further innovate and scale hydrogen fuel cell technologies across a range of commercial markets. Owning both fuel cell and hydrogen generation from electrolysis capabilities will enable the company to offer a full, differentiated hydrogen solution, from start to finish, seamlessly integrated for customers.

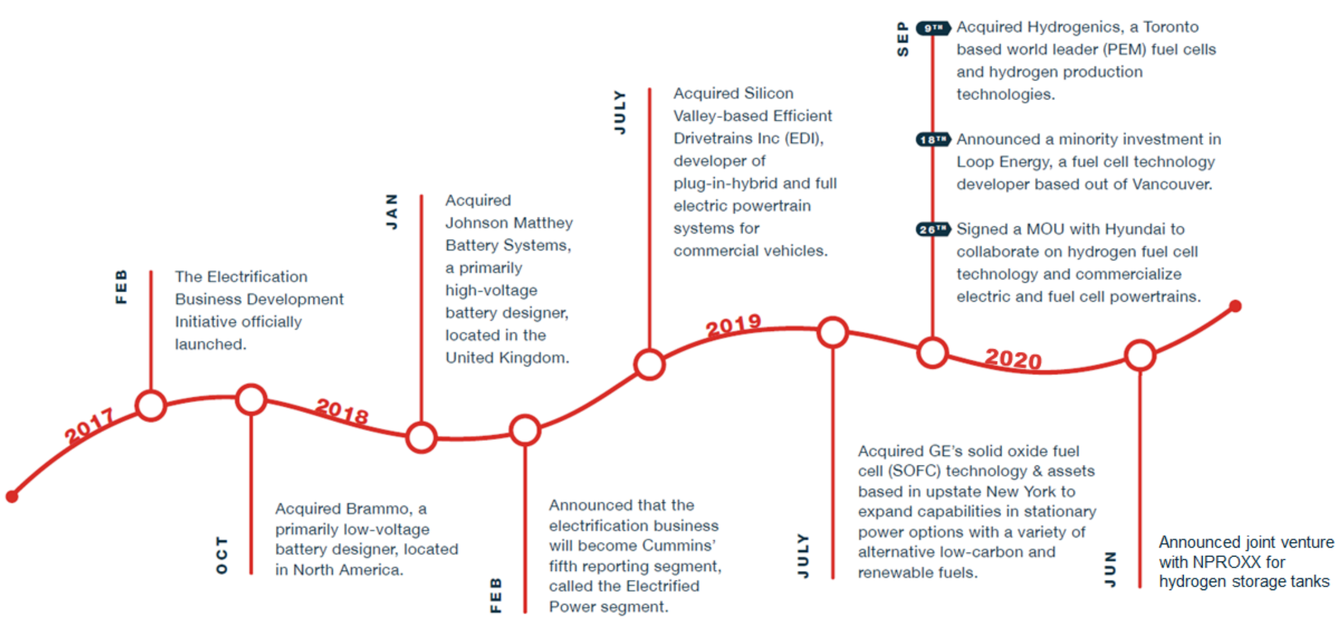
Hydrogenics' facilities, as well as its employees, were integrated into Cummins' fifth business segment, New Power. Since the acquisition of Hydrogenics, Cummins has dedicated a significant number of resources and capital to expand its operation in California.

Cummins Inc. and the New Power Segment

Cummins, a global power leader, is a corporation of complementary business units that design, manufacture, distribute, and service a broad portfolio of power solutions. The company's products range from diesel and natural gas engines to hybrid, electric, and fuel cell platforms, as well as related technologies, including battery systems, fuel systems, controls, air handling, filtration, emission solutions, and electrical power generation systems. Cummins' vision is innovating for its customers to power their success. Cummins does this by investing in a range of technologies from diesel and natural gas internal combustion engines to fully electric and fuel cell solutions.

Cummins' expertise in alternative power technologies is rooted in more than 20 years of research, development, and strategic partnerships. Since 2017, Cummins has significantly ramped up its capabilities to offer a full, differentiated electrified power solution, from start to finish, seamlessly integrated for customers (Figure 2). New Power is Cummins' fifth business segment, focused on electrified power and fuel cell and hydrogen technologies. Cummins works to design and manufacture alternative power sources, including electrified power, fuel cell, and hydrogen technologies. Applications include school buses, transit buses, light-commercial vehicles, medium-duty trucks, trains, off-highway applications, as well as hydrogen production technologies.

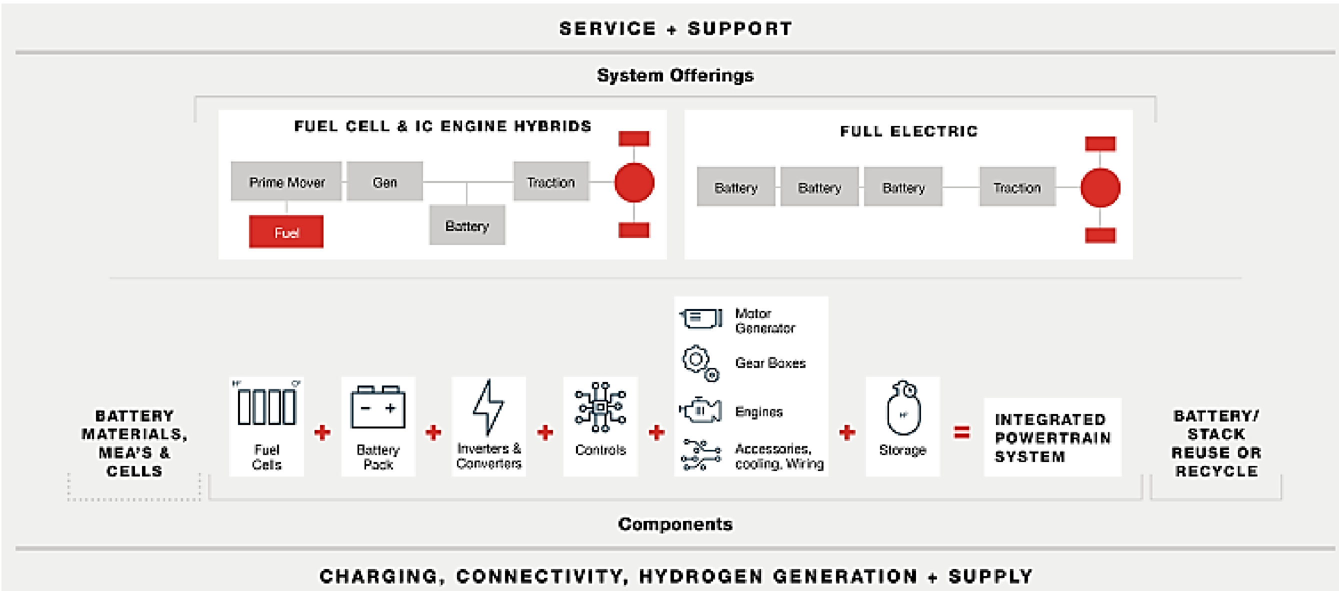
Figure 2: Cummins New Power Journey



Source: Cummins Inc.

Cummins New Power provides a portfolio of electrified, fuel cell, and hydrogen power solutions, as well as some of the most critical components that have the largest effect on performance, quality, and cost to deliver the most value to its customers (Figure 3).

Figure 3: Cummins Turnkey Fuel Cell and Electrified Power Systems



Source: Cummins Inc.

Cummins New Power organization spans the globe with major operations in North America, Europe, and Asia. In the United States, Cummins New Power's footprint is rooted in Columbus, Indiana, and in California, where facilities in Milpitas and West Sacramento provide 48,000 square feet for system development, vehicle integration, and low-volume production.

Figure 4: Cummins New Power Capabilities Map

Source: Cummins Inc.

Cummins has a 100-year-long track record of delivering leading power solutions. Notable technology commercialization successes include:

- More than 80,000 Cummins Westport 6- to 12-liter spark-ignited automotive natural gas engines in service worldwide today in commercial transportation application.
- More than 600 electrolyzer installations around the world, including the world's largest electrolyzer system (20 megawatt) in Canada for Air Liquide.
- More than 400 electric school buses, powered by a Cummins fully electric drivetrain, have been ordered to date from Blue Bird Corporation, a school bus manufacturer.
- More than 200 buses equipped with fuel cell power modules from Hydrogenics are in operation in China, including transit buses with Yutong and Foton.
- Partnership with GILLIG to integrate the Cummins electrified powertrain with the proven low-floor platform bringing the most advanced zero-emission bus to the market.
- A 10-year agreement to supply Alstom Transport with hydrogen fuel cell systems for regional commuter trains.

Project Description

Hydrogenics USA proposed demonstrating to the CEC the technical and market viability of an advanced zero-emission hydrogen fuel cell propulsion technology purposely designed and developed for medium- and heavy-duty mobility application. This proposed advanced propulsion technology was to expedite commercialization of hydrogen fuel cell medium- and heavy-duty commercial vehicles by significantly reducing development, integration, and production costs of building fuel cell hybrid vehicles.

The requested CEC funding was to be matched by Hydrogenics' and New Flyer Industries' (New Flyer) funding to integrate the proposed advanced fuel cell propulsion technology into New Flyer's 40-foot battery transit bus platform, Xcelsior, and demonstrate it in real-world transit operation.

The project was kicked off in August 2015 but faced a series of challenges typical in the earlier phase of the fuel cell industry:

- Longer-than-expected contract negotiations with New Flyer and Siemens, the two major subcontractors, delayed the start of the design work. The New Flyer agreement was executed in April 2016, and Siemens' agreement was executed in July 2016.
- Repeated issues with the prototype Celerity Plus fuel cell power system and the A123 Systems high-voltage battery delayed the demonstration in real-world transit operation.
- Upon Cummins' acquisition of Hydrogenics, the Hydrogenics USA organization was integrated into Cummins. This integration led to additional delays as both organizations worked on integration activities.
- Shortly after Cummins' acquisition of Hydrogenics, the responsibility to complete the project was passed onto Cummins Electrified Power NA Inc., a wholly owned subsidiary of Cummins with operations in California. Several system upgrades were required to improve the performance of the Hydrogenics Advanced Fuel Cell Bus.
- Issues with cooling the Celerity Plus fuel cell power system at high temperature and low humidity limited fuel cell power output and ultimately prevented the completion of the demonstration in real-world transit operation.

Despite facing these challenges, Hydrogenics successfully built an advanced fuel cell transit bus, demonstrated it in real-world transit operation, and captured several critical lessons that are advancing Cummins' product design today. The funding from the CEC was critical to advancing hydrogen and fuel cells in the heavy-duty vehicle market and helped Hydrogenics position itself to be acquired by Cummins. Looking forward, Cummins is using this project as a building block for its next-generation, heavy-duty fuel cell electric powertrains and is committing significant resources in California to bring its fuel cell technologies to market.

Statement of Work Summary

Project Goals and Objectives

This agreement sought to demonstrate the technical and commercial viability of an advanced hydrogen fuel cell propulsion system that will lead to market adoption and product commercialization.

The objectives of this project were to:

- Demonstrate integration and development processes of the proposed advanced fuel cell propulsion system into New Flyer's 40-foot battery transit bus platform.

- Conduct 12-month field demonstration to verify the performance of the proposed fuel cell technology and to collect performance information.
- Document the bus assembly process.
- Reduce greenhouse gas emissions during the demonstration period.

Tasks and Key Deliverables

The project was broken down into the following five tasks. Each included several key deliverables.

Task 1: Administration

Task goals were to attend a kick-off meeting, critical project review meetings, and the final meeting; provide monthly progress reports and the final report; and identify and obtain matching funds, required permits, and execute subcontracts. This task included several formal and informal deliverables that were provided to the Commission agreement manager throughout the project.

Task 2: Design, Procure, and Build

Task goals were to assess, design, procure, and build the bus before releasing the bus to SunLine Transit Agency (SunLine) for demonstration. The key deliverables were a summary report with photographs.

Task 3: Test, Validate, and Ship

Task goals were to perform testing and validation before shipment and deliver the bus to SunLine. The key deliverable was a summary report with photographs.

Task 4: Demonstration

Task goals were to provide training, monitor performance, and conduct and support bus demonstration. The key deliverable was the final report.

Task 5: Data Collection and Analysis

Task goals were to collect operational data from the project, analyze those data for economic and environmental effects, and include the data and analysis in the final report. The key deliverable was the data collection information and analysis to be included in the final report.

CHAPTER 2: Fuel Cell Bus Design

The advanced fuel cell propulsion technology is a result of a joint development between Hydrogenics and Siemens to advance commercialization of fuel cell hybrid medium and heavy-duty commercial vehicles by significantly reducing the development and integration costs of building fuel cell hybrid vehicles. This advanced zero-emission propulsion technology developed by Hydrogenics is named "Celerity Plus" — the first fuel cell power system designed, developed, and dedicated for medium- and heavy-duty commercial vehicles and pretested and preinterfaced to an electric hybrid drive provided by Siemens.

System Specifications

The Hydrogenics Advanced Fuel Cell Bus is based on the New Flyer Xcelsior electric bus platform depicted in Figure 5. It is a hybrid electric vehicle, blending power from an 80-kilowatt-hour high-voltage battery and the 60-kilowatt (kW) Hydrogenics Celerity Plus fuel cell power system. The Celerity Plus operates as a range extender running as required to sustain the battery charge, further extending the vehicle range.

Figure 5: New Flyer Xcelsior Electric Bus Platform (left) and Hydrogenics Celerity Plus Fuel Cell Power System (right)

Source: NFI Group Inc. and Cummins Inc.

Specifications of the Hydrogenics Advanced Fuel Cell Bus are summarized in Figure 6 below.

Figure 6: Hydrogenics Advanced Fuel Cell Bus Specifications

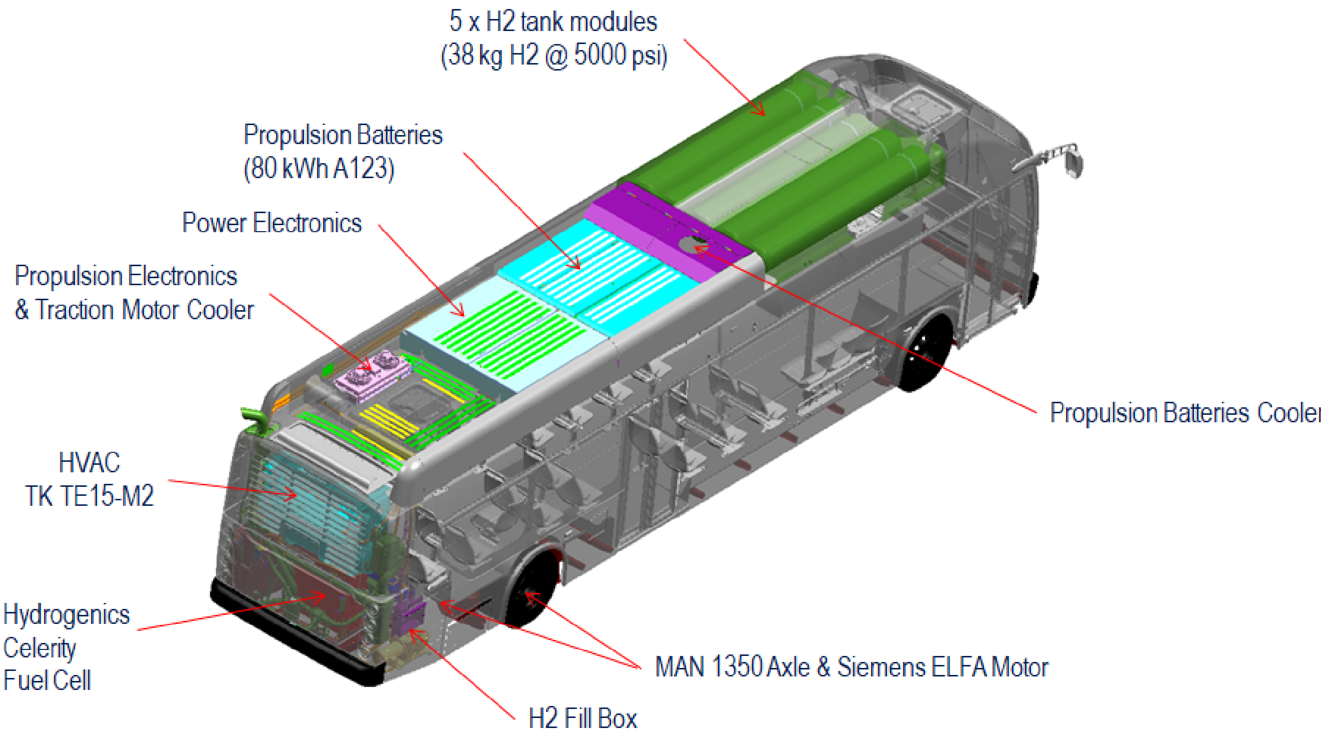
Attribute	Specification/Description
Base Vehicle	New Flyer Xcelsior XE40 Electric Bus Platform
Bus Length	41' / 12.50m
Capacity	39 seated, 41 standees
GVWR	44,533 lbs.
Curb Weight	31,768 lbs.
Front Axle Weight	11,294 lbs.
Rear Axle Weight	20,474 lbs.
Traction Motor	Siemens Permanent Electromagnetic Motor (PEM)
Rated Power	160 kW
Max Torque	1019 Nm / 750 ft-lb
Transmission	Direct Drive
Hydrogen Fuel Cell	Hydrogenics Celerity Plus Fuel Cell Power System Rated: 60kW
High Voltage Battery	A123 Systems 80 kWh Lithium iron Phosphate (LFP) Battery
Hydrogen Storage	38 kg @ 5000 psi (350 bar)
Max. Vehicle Speed	55 mph (all accessories running @ GVWR, APTA Guideline Alternative)
Estimated Range	300 miles based on standard Altoona test profiles
Acceleration, Gradeability and Braking	Compliant to APTA Procurement Guidelines

Source: Cummins Inc.

Fuel Cell Propulsion System Layout

The advanced fuel cell propulsion technology consists of the following subsystems: fuel cell power system, power electronics module, traction motor, hydrogen fuel system, battery energy storage, electric accessories system, and driver interface and control. Figure 7 below shows the layout and placement of these main subsystems and components of the bus.

Figure 7: Hydrogenics Advanced Fuel Cell Bus Major Components Layout



Source: NFI Group Inc.

Each of the subsystems is described in more detail below.

Fuel Cell Power System

The Celerity Plus is an "all-in" fuel cell power system with the following technical features and benefits for accelerating commercialization of fuel cell-powered medium- and heavy-duty vehicles (Figure 8 and Figure 9).

Figure 8: Hydrogenics Celerity Plus Technical Features and Benefits

Innovative Features	Commercialization Benefits
Optimal configuration for voltage and current: flexible modularity in 60kW	✓ Reliable power performance for MHD drive cycle that commercial vehicles can rely on ✓ Low stack current that further improves system efficiency. ✓ Compact modularity enables easy installation as a single unit for range extension or multiple units for prime power and thus simplifies design process for power.
Optimal configuration in dimensions to be easily installed in the engine bay of a commercial truck.	✓ Minimize/eliminate the time and effort spent on modifying the truck chassis and frame rail to fit the fuel cell power system and thus shorten development and production time and cost of a fuel cell powered vehicle ✓ Easier to access, remove and to maintain and thus lower the maintenance time and cost for vehicle operators ✓ Lower development cost, capital cost of vehicle and lower maintenance cost lead to lower TCO of a fuel cell powered vehicle => more affordable for commercialization
Celerity is a highly integrated system with all major components packages into an IP-rated enclosure, including an advanced cold-weather package, achieving storage capacity at -40ºC and system start-up at -10ºC. Also included is reverse current protection and a fully integrated air delivery blower to provide optimum oxygen flow for low-pressure stack operation.	✓ Minimize/eliminate the time and effort for integrating peripheral components around the fuel cell power module which are usually required for other fuel cell power modules that are currently available in the market.

Source: Cummins Inc.

Figure 9: Hydrogenics Celerity Plus Technical Specifications

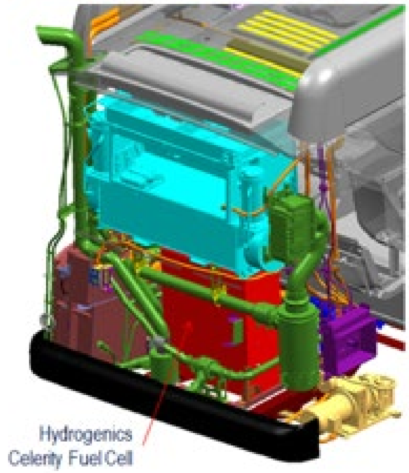
Net Power	60 kW
Performance	
Operating DC Voltage Range	300 to 640 V
Operating current	0 to 200 A
Physical	
Weight (dry)	275 kg
Length x Width x Height (mm)	800 x 375 x 980
Fuel	Hydrogen (Commercial grade per ISO/TS 14687-2:2008(E))
Oxidant	Air
Coolant	
Deionized Water	100%
Ethylene Glycol/Deionized Water	60/40%
Operating Conditions	
Coolant Outlet Temperature	45 – 65 °C
Hydrogen Supply Pressure	515 – 790 kPa
Air Supply Pressure	Ambient
Additional Features	
Control interface	CANbus J1939
Enclosure	IP-rated

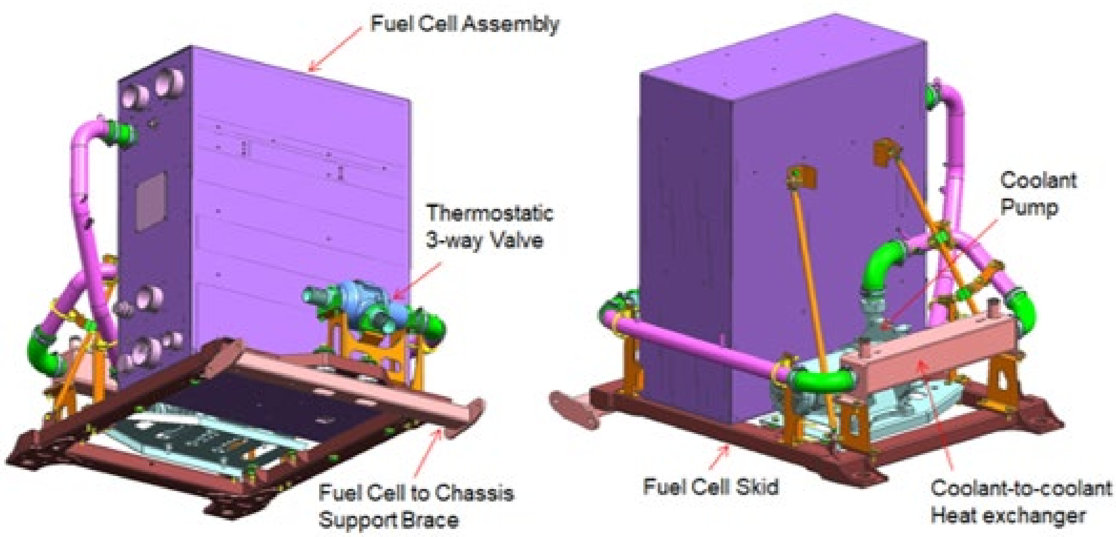
Source: Cummins Inc.

The Celerity Plus fuel cell power system is mounted in a subframe assembly that is mounted in the conventional engine bay of the bus platform (Figure 10 and Figure 11). Components installed on the subassembly include:

- Fuel cell assembly (coolant pump, radiator, tank, piping, air intake system, and exhaust).
- Power steering assembly (tank, motor, pump, and hoses).
- Air-conditioning assembly (motor, compressor, dryer, condenser, and hoses)
- Coolant loop connection to cabin.
- Fuel cell coolant pump located forward of the fuel cell.
- Heat exchanger for colder weather operation and recovery of waste heat.
- Process piping for coolant plumbing, coolant flow control and air intake, and fuel cell exhaust process piping.

Figure 10: New Flyer Subassembly Design and Details for Hydrogenics Celerity Plus





Source: NFI Group Inc.S

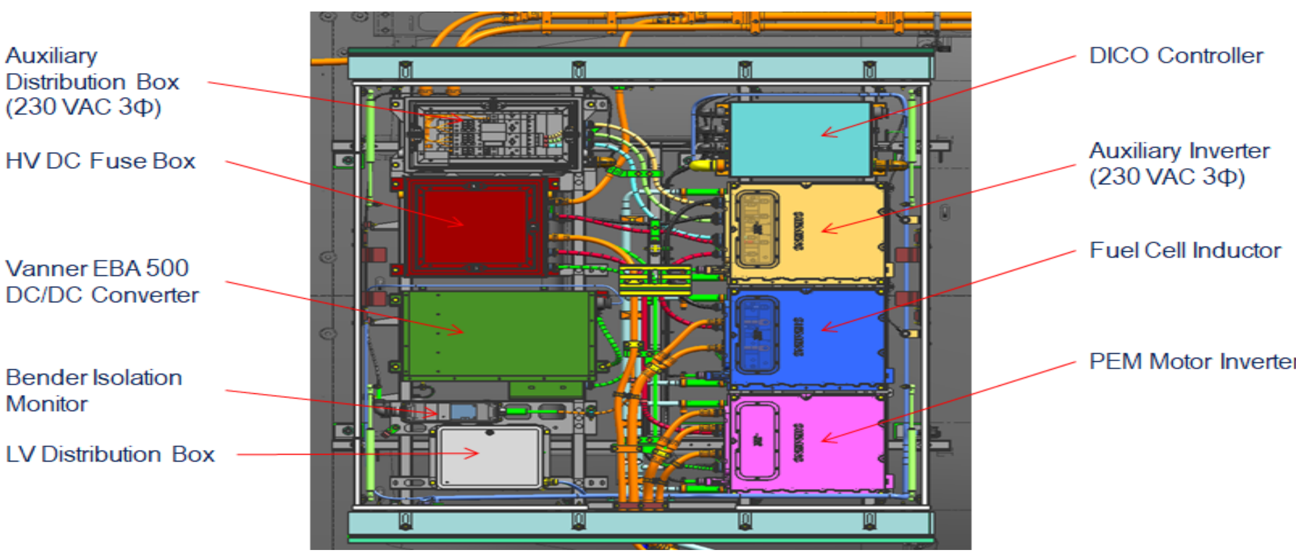
Figure 11: Hydrogenics Celerity Plus Subassembly Installed in Bus Engine Bay

Source: NFI Group Inc.

Power Electronics Module

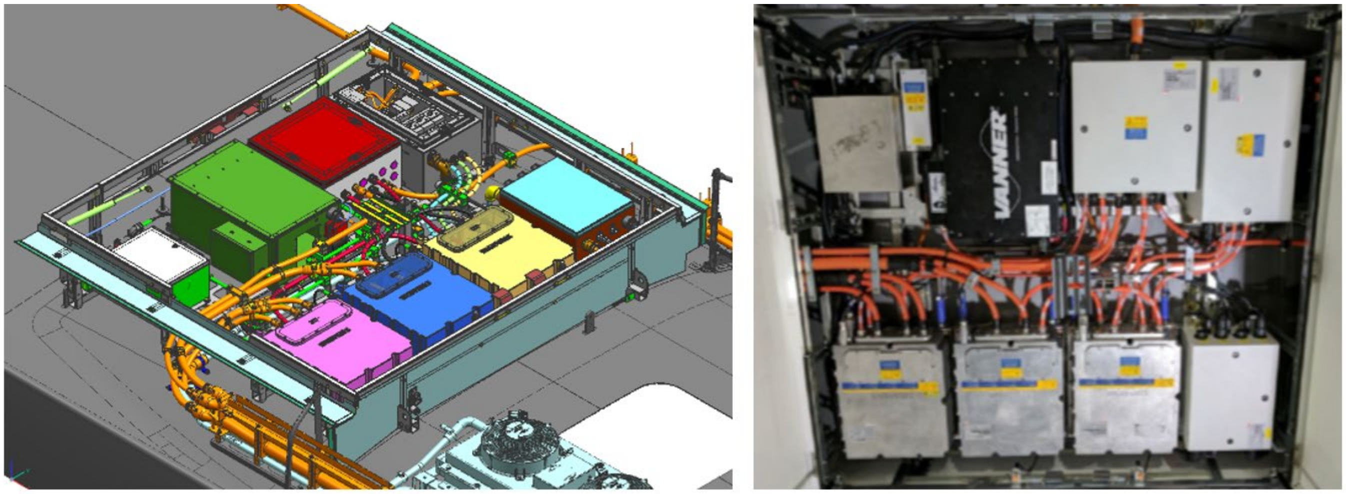
The basic Siemens drive system consists of high-efficiency, liquid-cooled Siemens inverters, inductor, drive motor, auxiliary inverters, control unit, and power cables. With the exception of the traction motor, the basic system is packaged in the rooftop power electronics module and is the central location for power conversion and distribution for the fuel cell vehicle (Figure 12 and Figure 13). The entire module is built, wired, and pretested as a subassembly before installation on the bus. The high-voltage battery packs are connected directly to the high-voltage electrical bus, and the Celerity Plus fuel cell power system interfaces to the power electronics assembly through a direct connection with the Siemens inductors, positioned at the bottom right of the power electronics module.

Figure 12: Power Electronics Module Design



Source: NFI Group Inc.

Figure 13: Power Electronics Module Installed on Bus

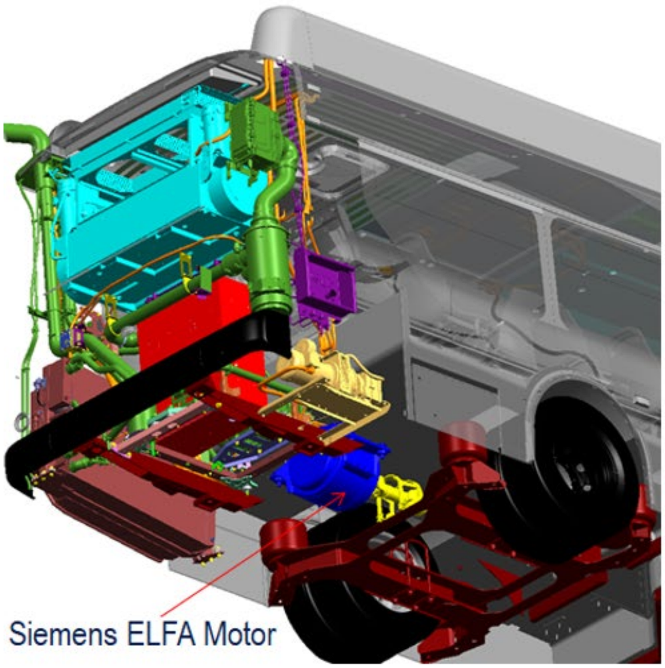


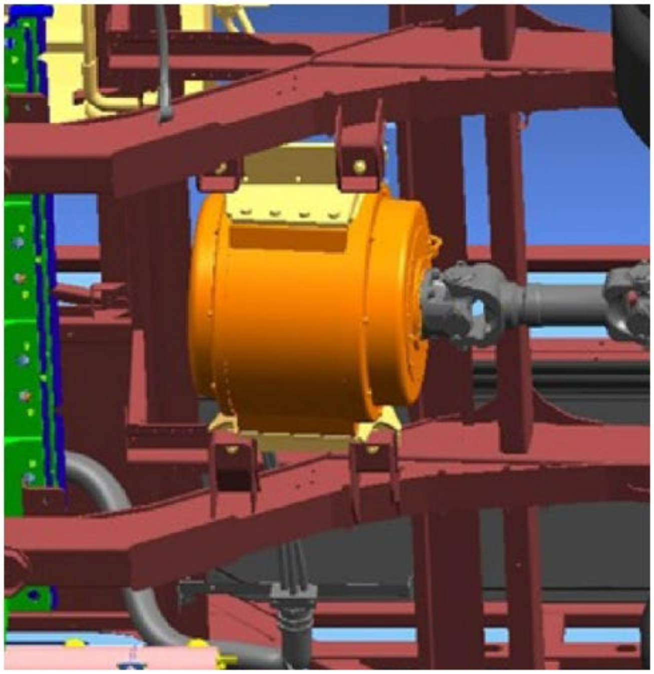
Source: NFI Group Inc.

Traction Motor

The Siemens traction motor is a liquid-cooled, high-efficiency permanent excited synchronous type motor. Due to the size, torque, and speed, the traction motor is mounted directly on the rear axle differential without a gearbox. The function of the traction motor is to convert the electrical power (voltage and current) from the fuel cell and battery system through the inverter into mechanical power with the required torque and speed range to propel the bus. Figure 14 below shows the drive motor installation and direct connection to the differential.

Figure 14: Drive Motor Bus Chassis Integration Design



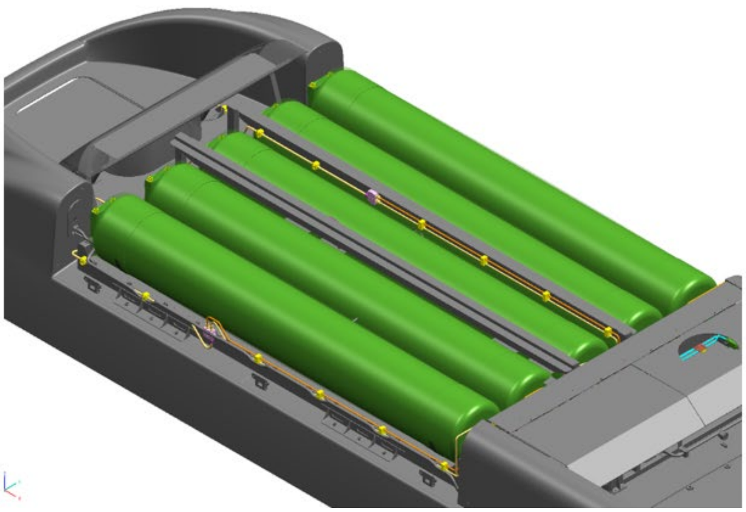


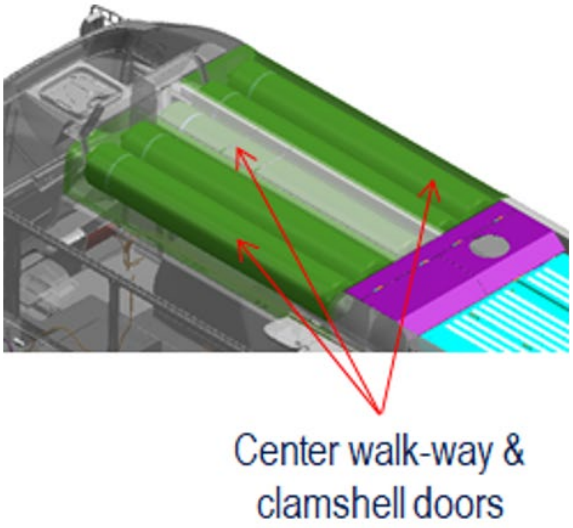
Source: NFI Group Inc.

Hydrogen Fuel Storage

The hydrogen fuel storage system was designed and built by New Flyer and uses seven carbon fiber Type 4 high-pressure cylinders, with a total capacity of 38 kilograms (kg) at 350 bar (5000 pounds per square incy [psi]) enough to support a 300-mile range, depending on driving conditions (Figure 15).

Figure 15: Hydrogen Fuel Storage System From New Flyer

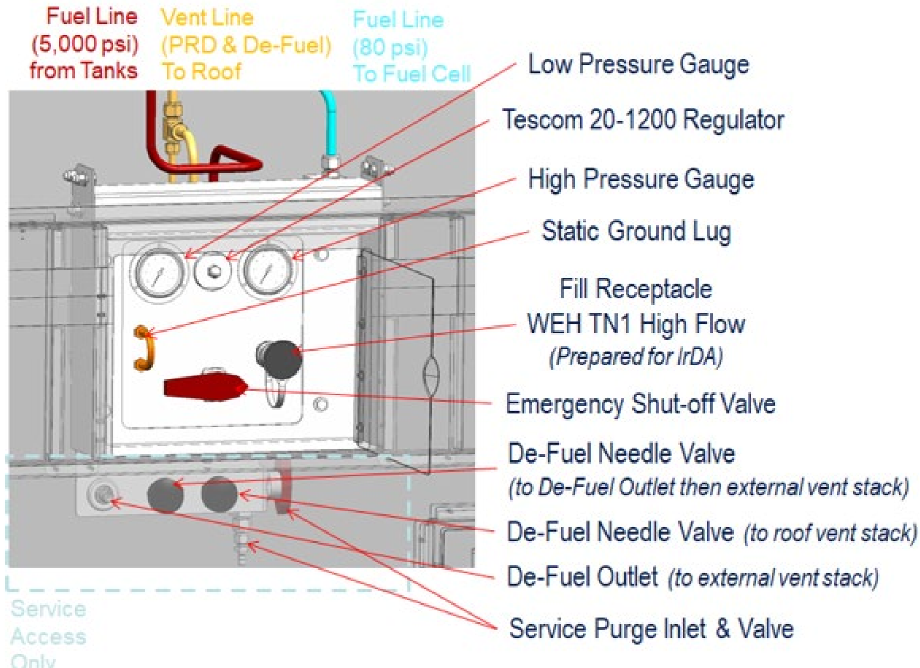




Source: NFI Group Inc.

The hydrogen fuel storage system is installed on the roof of the bus. The fueling port and interface are on the right side behind the rear wheel (Figure 16).

Figure 66: Hydrogen Fuel Storage System Installed on Bus

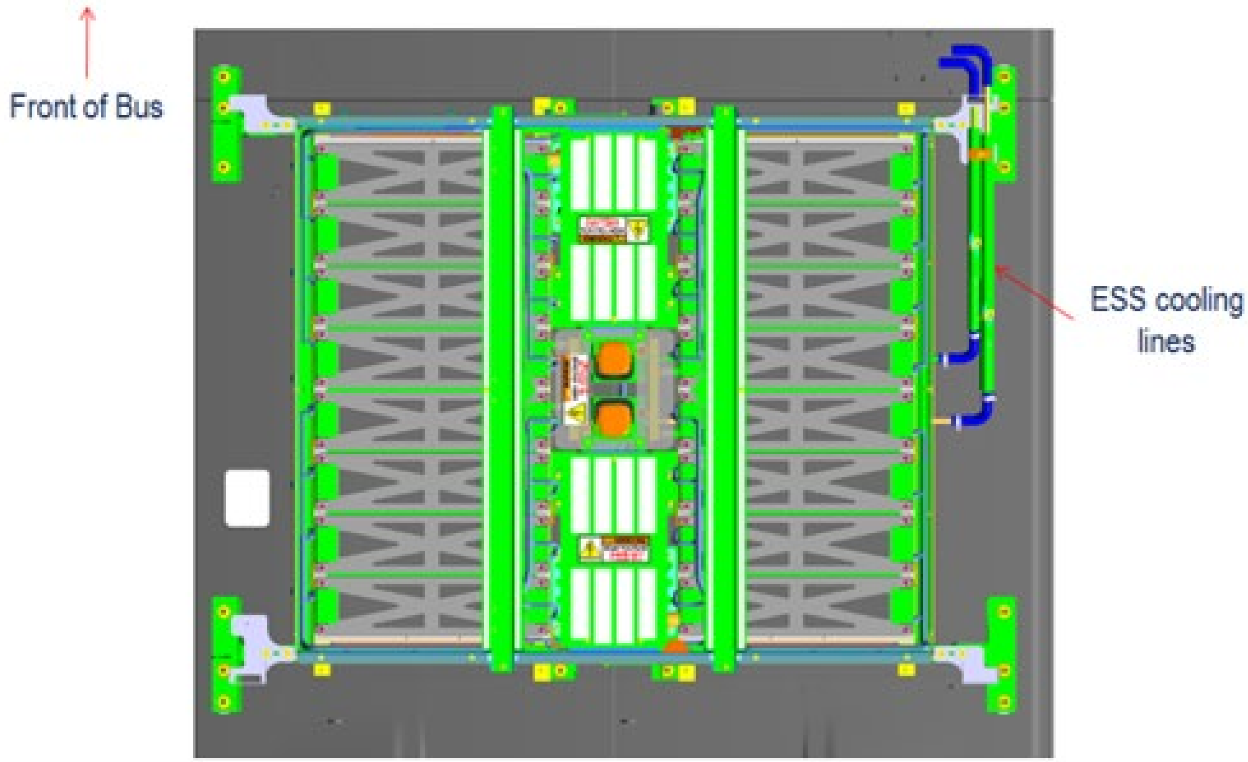


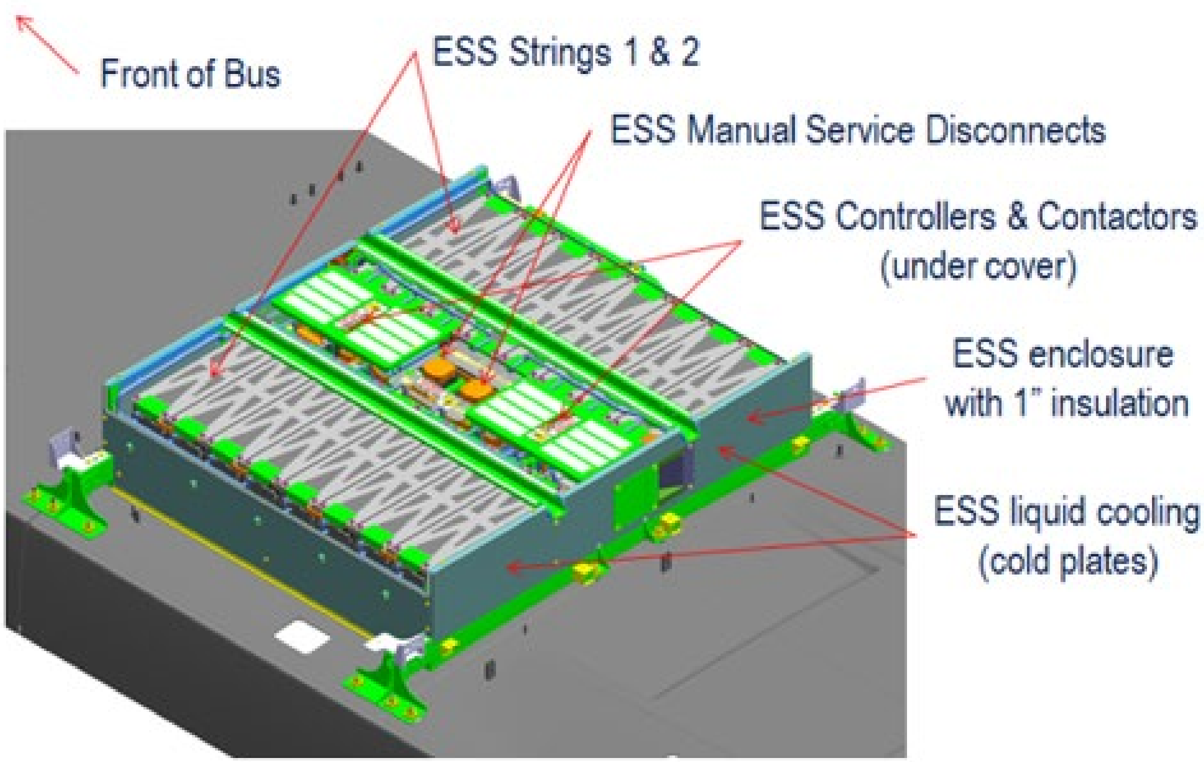
Source: NFI Group Inc.

Battery Energy Storage

New Flyer developed a new 80-kilowatt-hour (kWh), 600-volt direct current nominal battery energy storage system using U.S.-made A123 battery modules arranged in two pack strings with integrated cold plates and mounted in an environmentally sealed enclosure (Figure 17 and Figure 18). Low- and high-voltage cabling and power distribution, fuses, contactors, and two controller modules to manage each module connection are mounted between the pack strings. New Flyer's supervisory controller communicates with the A123 battery controllers and oversees all battery functions and all modes of operation.

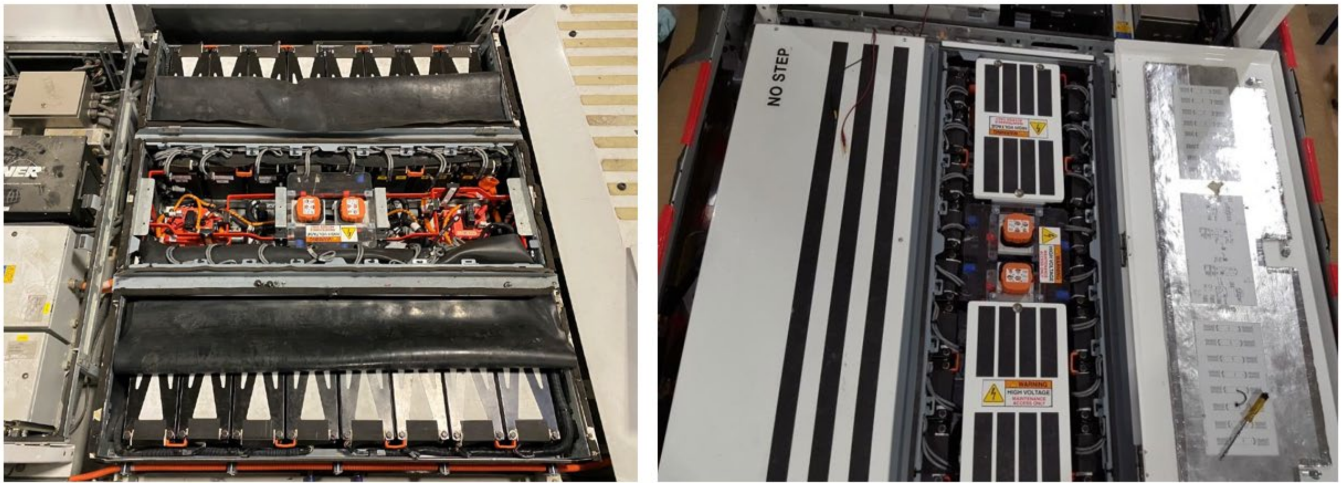
Figure 77: New Flyer Roof-Mounted Battery Energy Storage System





Source: NFI Group Inc.

Figure 88: New Flyer Battery Energy Storage System Installed on Bus

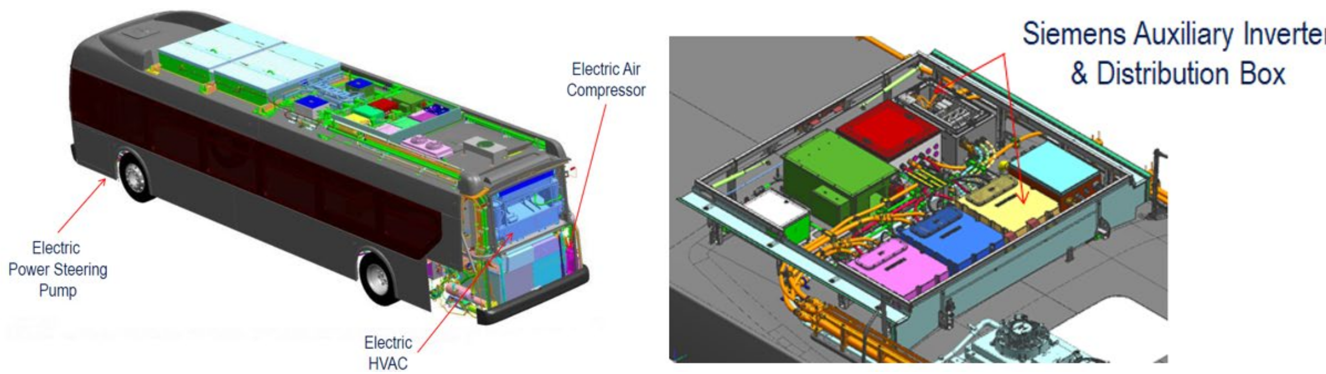


Source: NFI Group Inc.

Electric Accessories System

The Siemens auxiliary inverter provides 230 volts of alternating current via a high-voltage junction box to power accessory devices such as the power steering motor, air-conditioning motor, air brake pneumatic systems compressor, and fuel cell coolant pump (Figure 19).

Figure 99: Electric Accessories and Siemens Auxiliary Inverter Configuration

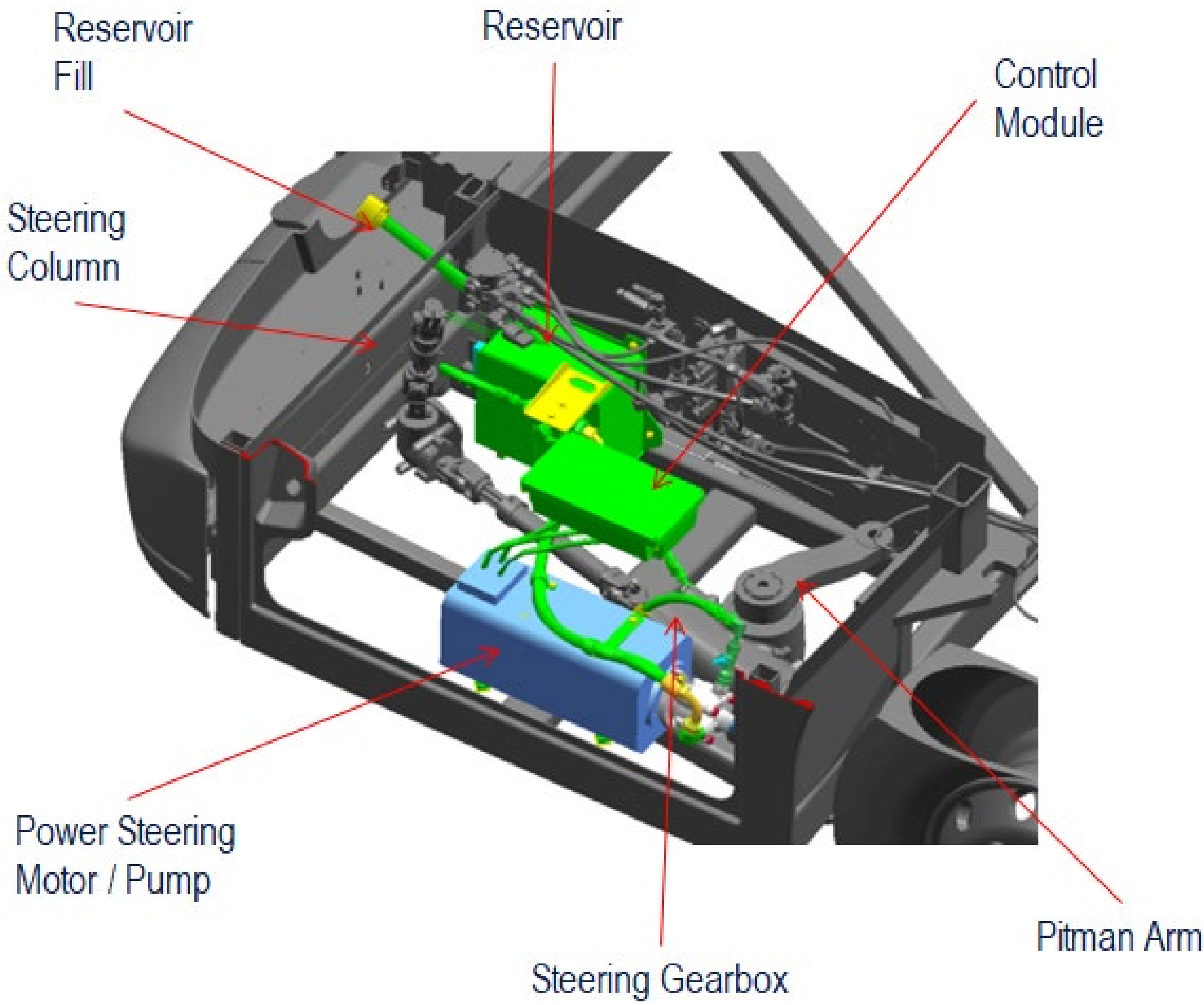


Source: NFI Group Inc.

Power Steering Assembly

New Flyer standard 24-volt direct current electric power steering pump is installed next to the steering gearbox in front of the bus (Figure 20).

Figure 20: Power Steering Assembly



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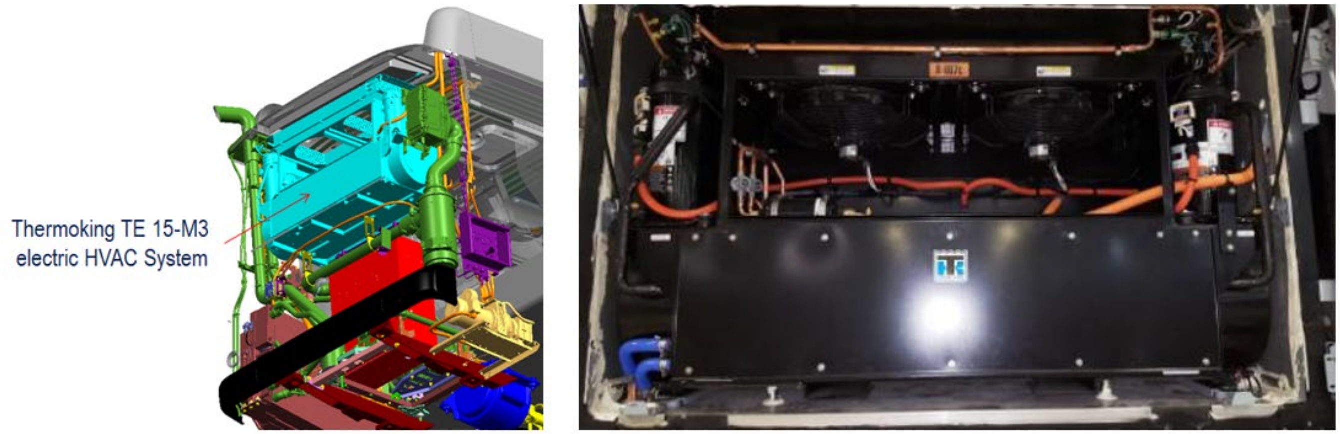
Source: NFI Group Inc.

Cabin Air-Conditioning System

The cabin air conditioning system is installed at the rear of the bus above the engine compartment (Figure 21).

Figure 21: Cabin Air Conditioning System

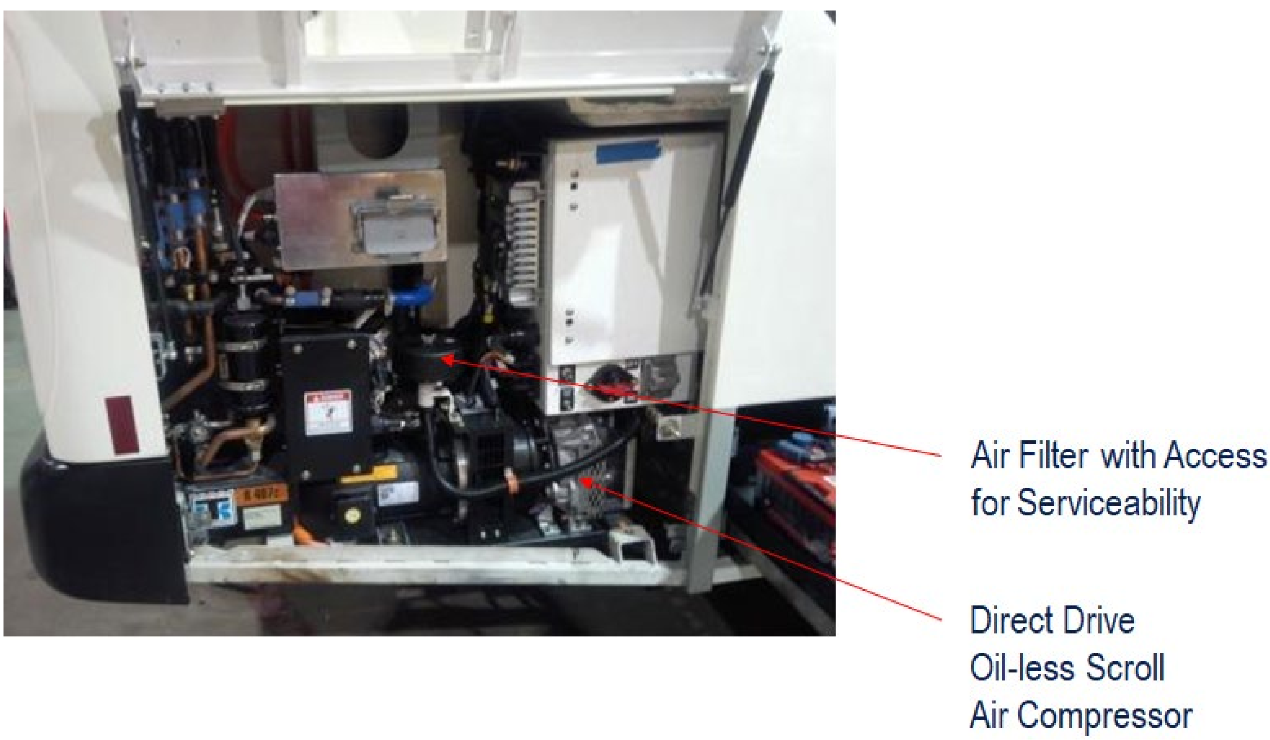


Source: NFI Group Inc.

Air Compressor Assembly

The air compressor is installed on the curbside section of the bus at the rear behind the service access panel (Figure 22). The electric compressor substitutes the original compressor linked to the diesel engine to provide compressed air to the braking and pneumatics systems.

Figure 22: Air Compressor Assembly

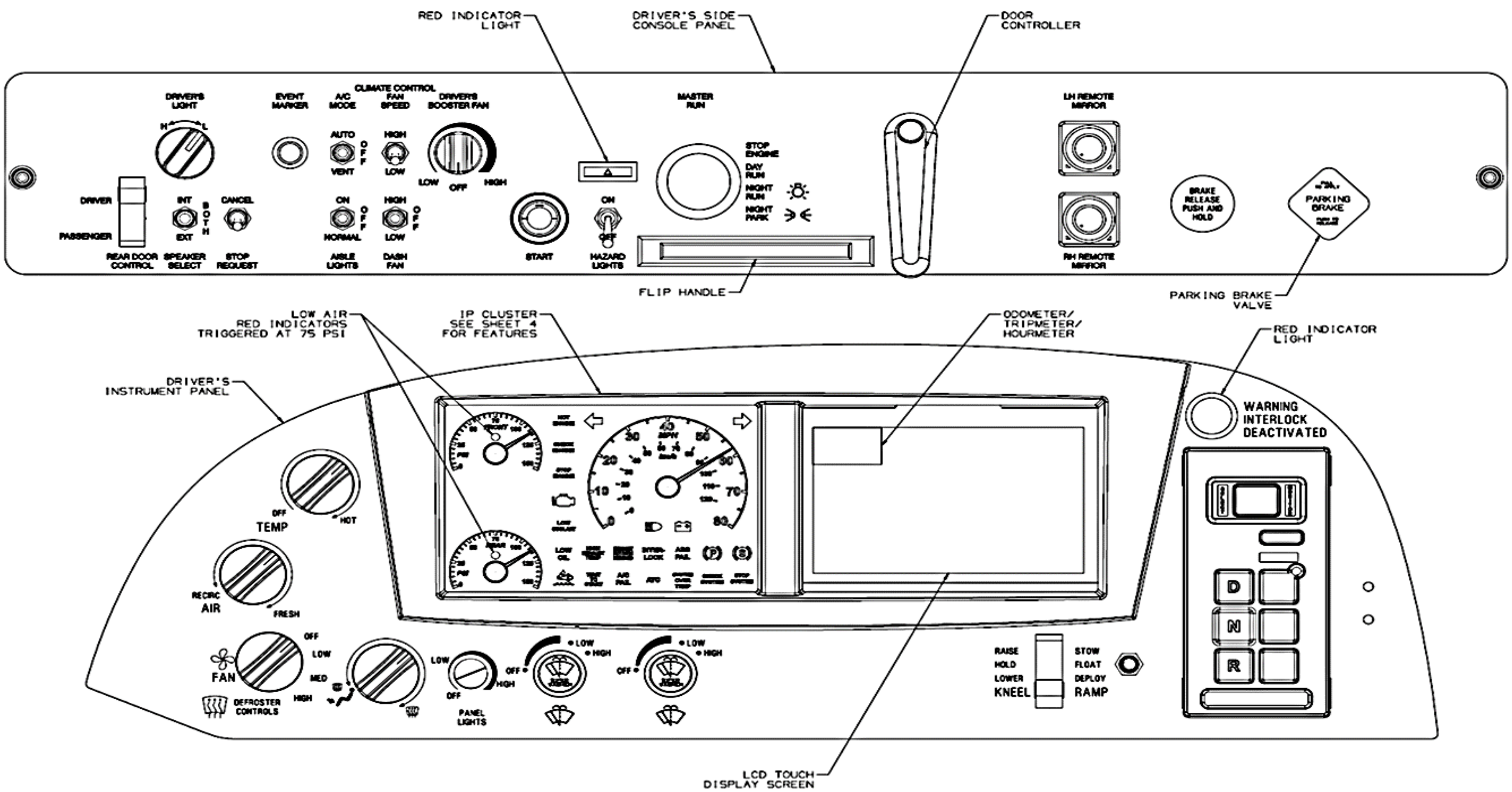


Source: NFI Group Inc.

Driver Interface and Control

Driver vehicle interface and controls are shown below in Figure 23 and is New Flyer's standard interface. Information such as vehicle speed, mileage, hydrogen pressure levels, battery state of charge, energy flows, faults and alarms, and shifter position are displayed. Signals such as throttle, brake, and shifter position are multiplexed and passed to the main electric vehicle control unit to control the overall drive system functions of the vehicle. The driver would be familiar with the controls and operation of the vehicle because they are similar to those of a conventional bus.

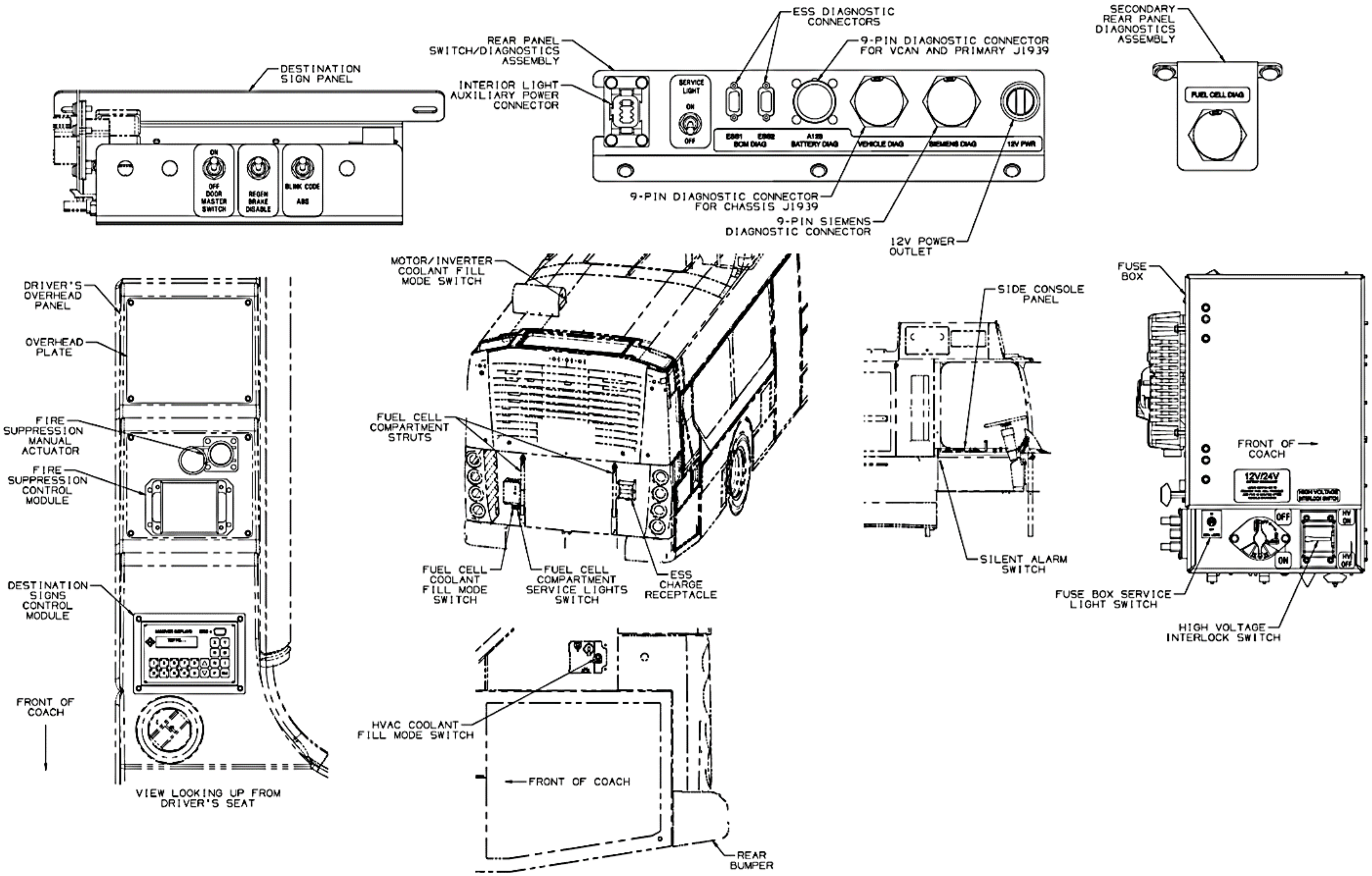
Figure 23: Driver Interface and Controls Layout



Source: NFI Group Inc.

Additional driver controls are available to the driver, as well as diagnostic J1939 interface connectors for the main drive components (Figure 24).

Figure 24: Diagnostic J1939 Interface Connectors

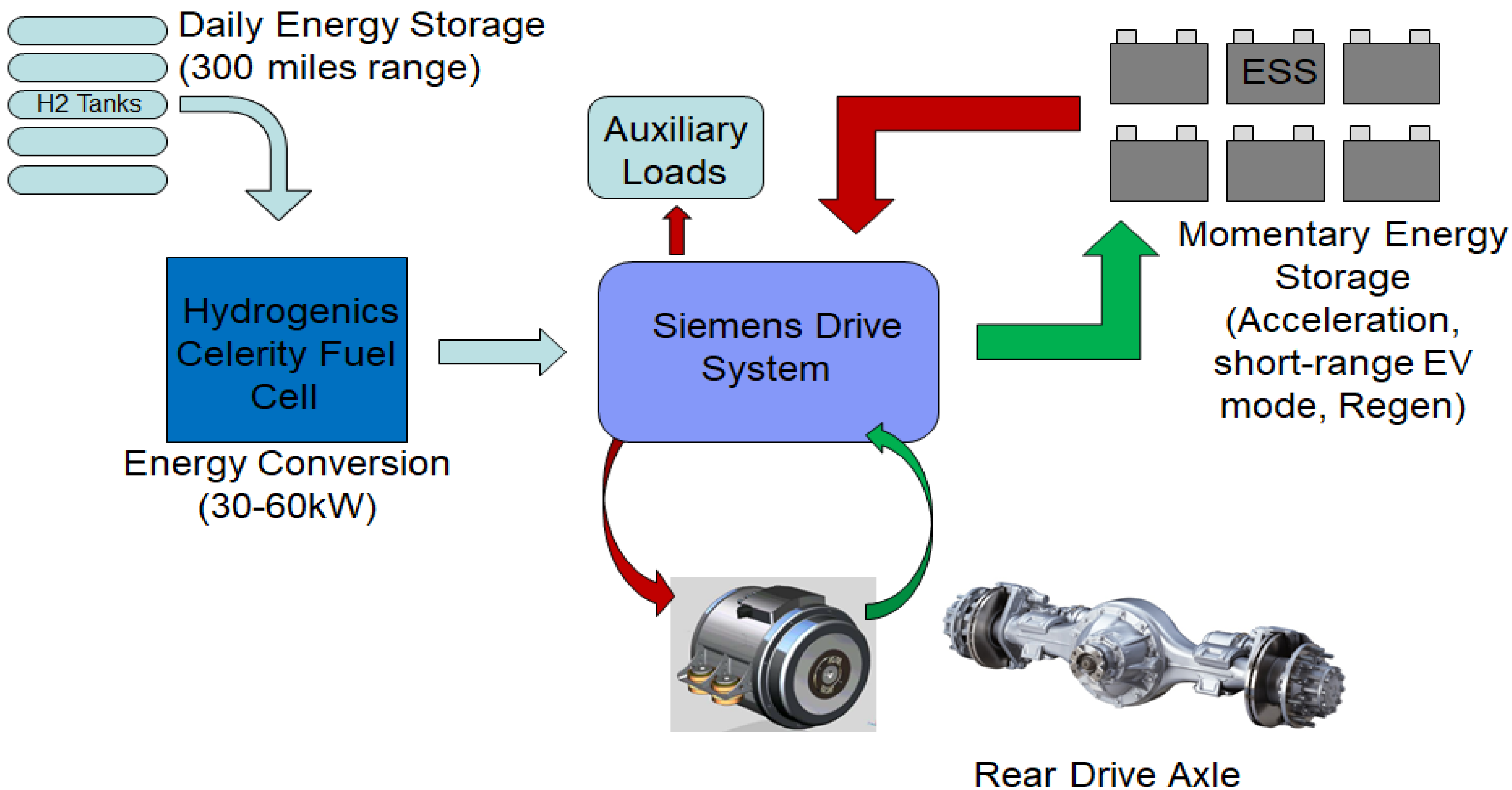


Source: NFI Group Inc.

Fuel Cell Truck Architecture

Figure 25 depicts the fuel cell bus system operation and the battery-dominant hybrid system architecture. The high-voltage battery provides power for acceleration, all-electric mode of operation, and energy recuperation from regenerative braking, thus improving overall system efficiency and providing benefits to mechanical brake service life. The Hydrogenics Celerity Plus fuel cell power system provides conversion of hydrogen energy stored in the roof-mounted fuel tanks to up to 60 kW of fuel cell power.

Figure 25: High-Voltage Bus Power Flow

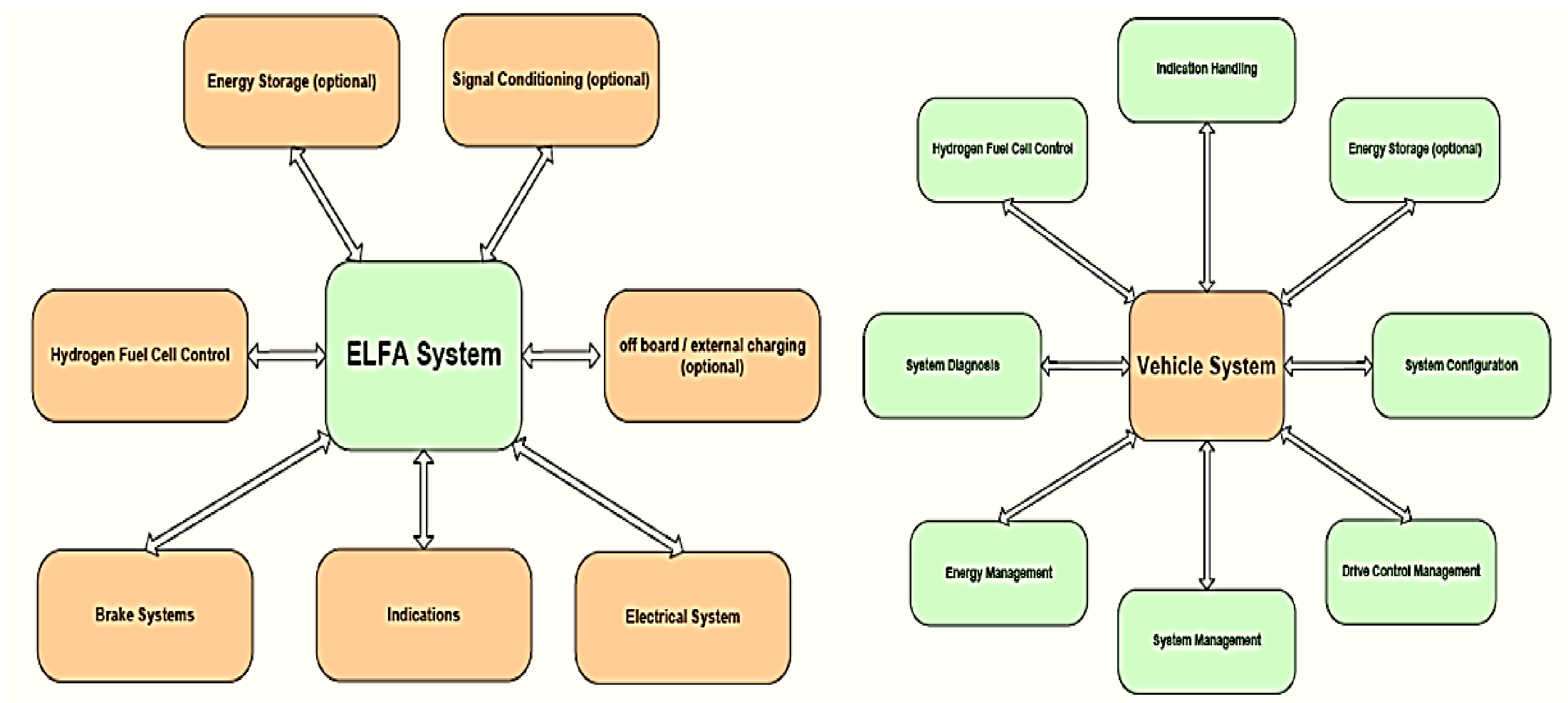


Source: NFI Group Inc.

Although the Celerity Plus is capable of load-following operation, New Flyer preselected two main operating points of 35 kW and 50 kW fuel cell power output. This was determined from numerical modeling of vehicle performance, based on control strategy. This control strategy optimizes the performance characteristics of the battery system, maximizes overall fuel efficiency characteristics of the fuel cell, and incorporates end-of-life performance characteristics of the fuel cell and battery system.

Figure 26 depicts the high-voltage architecture of the bus. It shows how components of the high-voltage system are connected to the main high-voltage direct current power bus. In the Hydrogenics Advanced Fuel Cell Bus configuration, the high-voltage battery pack is directly connected to the high-voltage bus with contactors, precharge and circuit protection fusing. The Celerity Plus fuel cell power system is connected to the drive system via a Siemens inductor.

Figure 26: Hydrogenics Advanced Fuel Cell Bus High-Level System Architecture



Source: NFI Group Inc

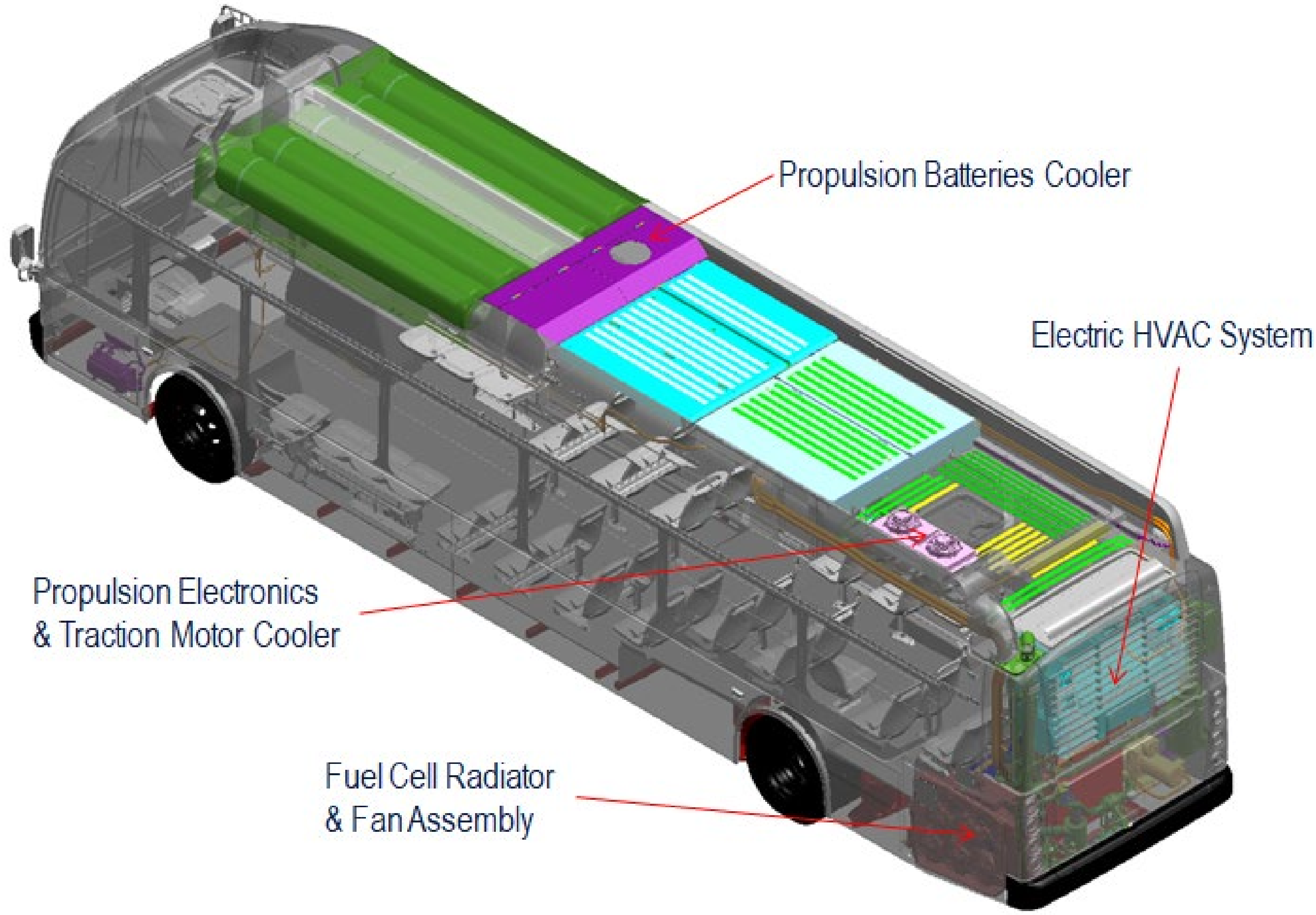
The air compressor, power steering motor, cabin air-conditioning motor, and fuel cell coolant pump are connected to the Siemens inverter via an auxiliary power distribution. An inverter provides the 24 volt direct current power to the standard low-voltage vehicle loads. Safety monitoring is performed by a high-voltage ground fault detector that constantly monitors if 600 VDC is properly isolated from the chassis to avoid any injury.

New Flyer's main supervisory control takes vehicle drivers' input from the vehicle controller area network (CAN) network, including any multiplexed discrete signals, and processes into control commands to the powertrain via J1939 CAN communication protocol. The New Flyer overall vehicle controller handles all system functions from master bus switch on to off, and all modes of operation from system startup, run, and shutdown.

New Flyer created a theory of operation control document based on Hydrogenics Celerity Plus documentation that describes New Flyer's bus control interface to the fuel cell drive system. The document captures vehicle-side interfaces to execute all fuel cell modes of operation such as startup, idle, run, standby, shutdown, freeze prep and faults and alarms processing and is used as a communication document between members of the fuel cell bus team. New Flyer has also developed a bus system level theory of operation document that describes in detail specific actions and sequence and timing duration of all devices in the overall drive system, starting from 24 Volt Direct Current system power up from SLI battery power, to high voltage battery pack connection, accessories engagement, fuel cell power up, all-electric and hybrid modes of operation and shutdown.

The Hydrogenics Advanced Fuel Cell Bus has three different cooling loops in order to optimize performance of the different components: 1) fuel cell coolant loop, 2) high voltage batteries coolant loop, and 3) power electronics coolant loop. The fuel cell coolant loop is optimized around the fuel cell optimal thermal set point and pressure (Figure 27). The high voltage battery packs are cooled with a chiller and the coolant loop in order to keep the batteries at their optimum operating temperature. The power electronics coolant loop is cooling the Siemens drive components (inverters, inductors, drive motor, and other accessories).

Figure 27: Hydrogenics Advanced Fuel Cell Bus High-Level Cooling Systems



Source: NFI Group Inc.

CHAPTER 3: Fuel Cell Bus Build, Integration and Testing

This chapter reviews the assembly and integration, commissioning and testing of the Hydrogenics Advanced Fuel Cell Bus. The advanced fuel cell propulsion technology was integrated by New Flyer with technical support from Hydrogenics and Siemens. The scope was to upgrade New Flyer's existing 40-foot battery transit bus platform with Hydrogenics' Celerity Plus fuel cell power system for range extension purposes.

Fuel Cell Bus Build and Integration Process

The Hydrogenics Advanced Fuel Cell Bus was built by New Flyer and Hydrogenics in the United States and Canada following the major steps described below.

Step 1: New Flyer Xcelsior XHE40 Bus Platform Build

The bus platform on which the Hydrogenics Advanced Fuel Cell Bus was built is based on the New Flyer Xcelsior XHE40 fuel cell electric bus that is currently in production with a competing fuel cell power system. For this project, New Flyer built a Xcelsior XHE40 fuel cell electric bus with a modified fuel cell compartment design and fuel cell cooling system to accommodate the Celerity Plus fuel cell power system. The bus was built at New Flyer in St. Cloud, Minnesota where all the major subsystems were built and installed in the second half of 2016. The bus was then delivered to New Flyer New Product Development Center in Winnipeg, Canada in November 2016 for the installation of the fuel cell (Figure 28).

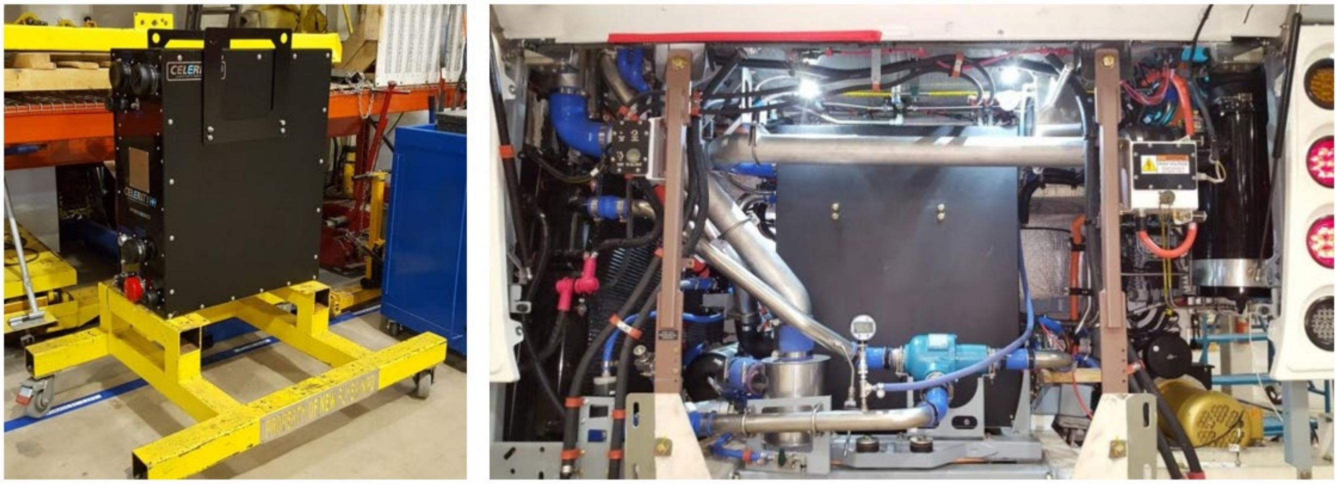
Figure 10: New Flyer Xcelsior XHE40 Bus Platform Delivery for Fuel Cell Integration

Source: NFI Group Inc.

Step 2: Hydrogenics Celerity Plus Fuel Cell Power System Integration

The Celerity Plus fuel cell power system was positioned on the fuel cell rack and installed in the engine compartment (Figure 29).

Figure 11: Hydrogenics Celerity Plus with Lifting Brackets (left) and Installed on Fuel Cell Rack in Engine Compartment (right)



Source: NFI Group Inc.

Step 3: Electrical Wiring and Cooling Lines Connection

The fuel cell thermal management system plumbing as well as the low and high voltage wiring was finalized (Figure 30).

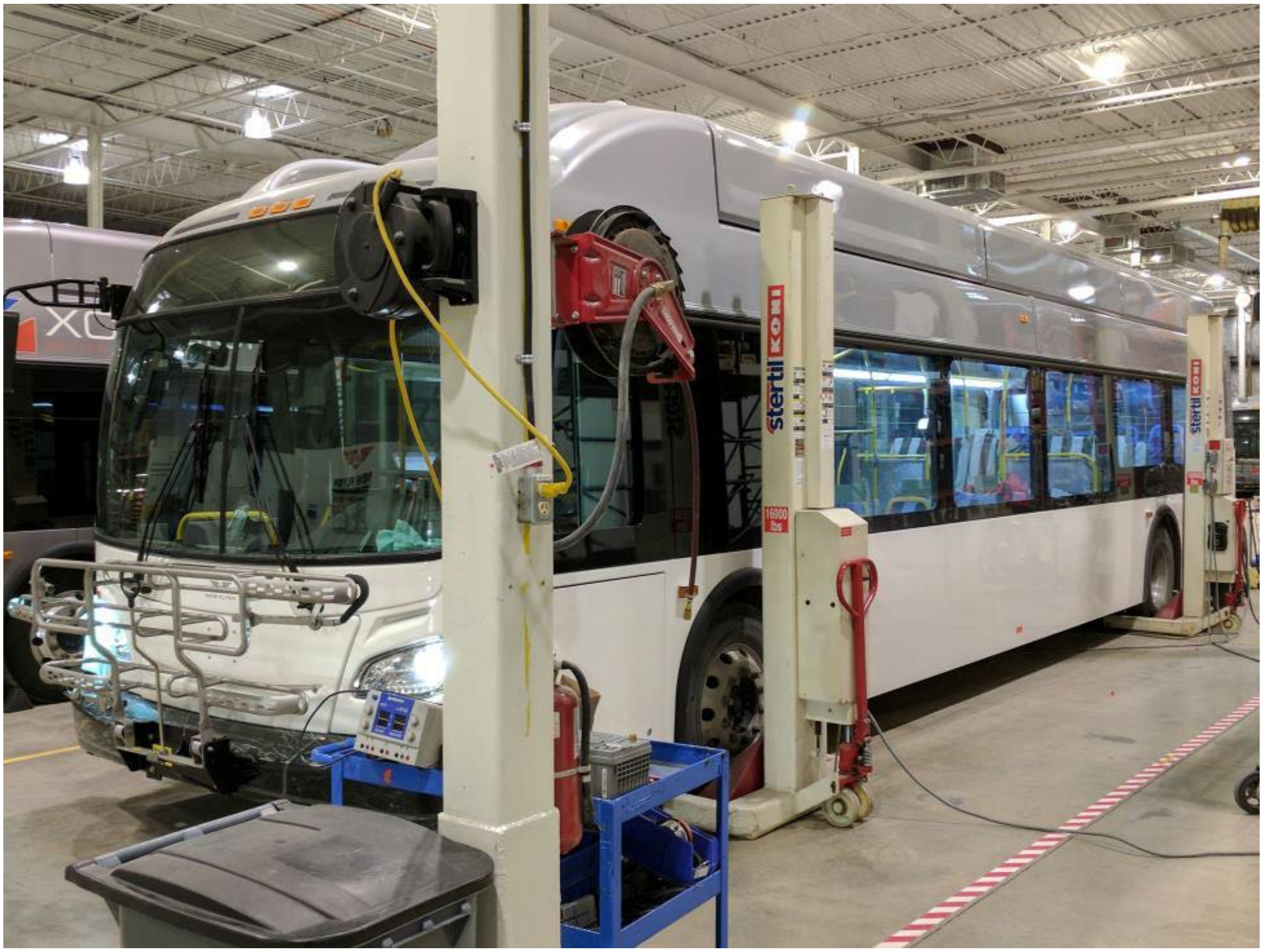
Figure 30: Details of the electrical wiring and cooling lines

Source: NFI Group Inc.

Step 4: Bus Build Completion

Minor rework and design improvements were carried out before the bus build was completed in the first quarter of 2017 (Figure 31).

Figure 31: Completed Hydrogenics Advanced Fuel Cell Bus

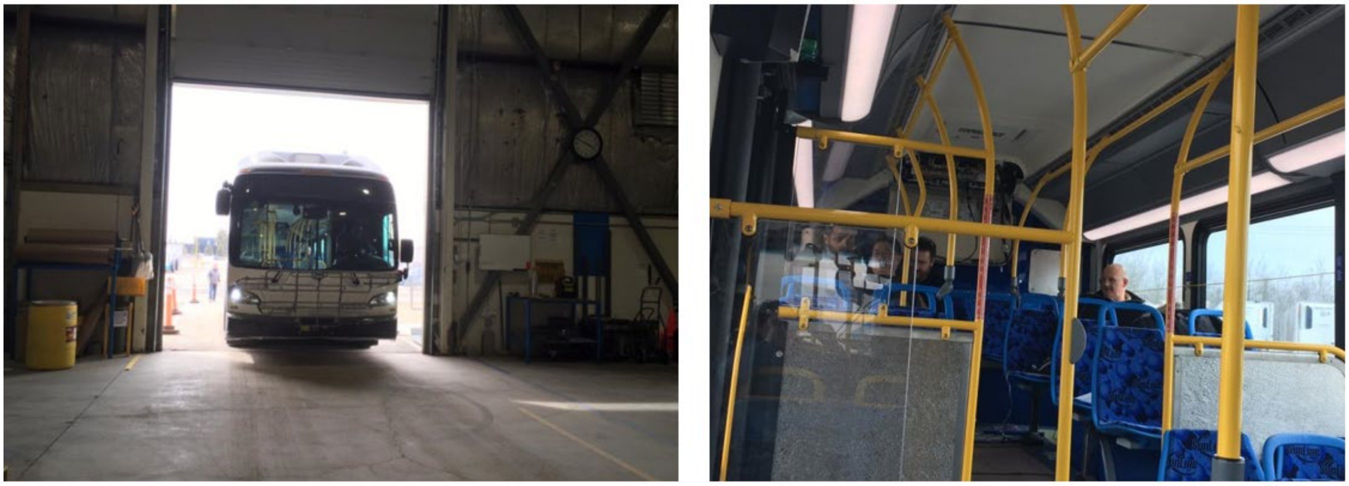


Source: NFI Group Inc.

Step 5: Bus Commissioning

Upon completion of the truck build, the fuel cell system and major subsystems were commissioned to troubleshoot any issues and optimize the controls and calibration between the fuel cell and powertrain. Functional tests of all the subsystems as well as the advanced fuel cell propulsion system were done next before the first key-on test of the Hydrogenics Advanced Fuel Cell Bus was completed. Initial bus commissioning was performed in February and March 2017. Lastly, a first drive of the vehicle was completed at low speed on March 23, 2017 (Figure 32).

Figure 12: Hydrogenics Advanced Fuel Cell Bus First Drive



Source: NFI Group Inc.

Performance Testing and Validation

Upon completion of the vehicle commissioning, the Hydrogenics Advanced Fuel Cell Bus underwent a series of test and validation activities to assess its performance and suitability for the fleet demonstration.

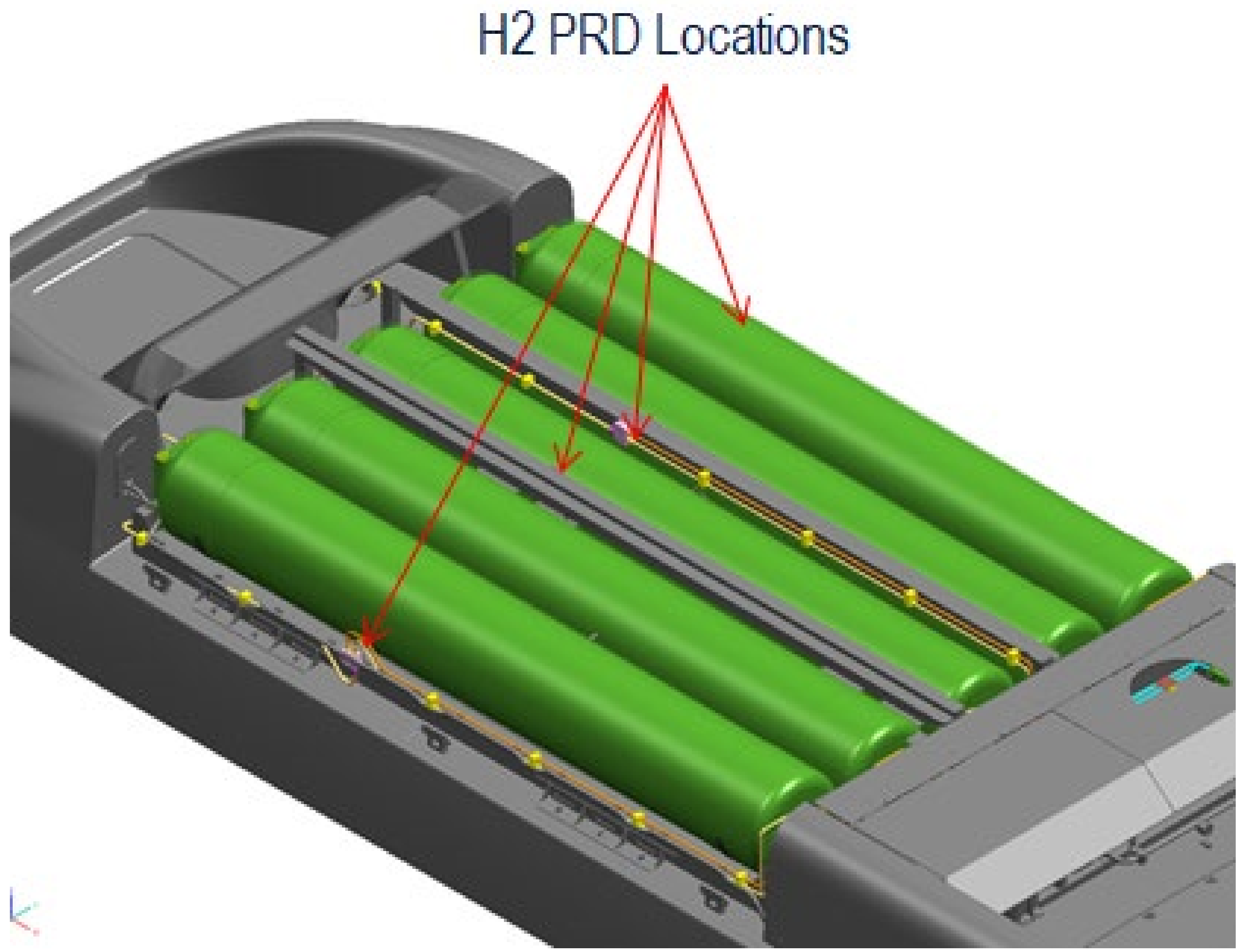
Vehicle Upgrades

New Flyer's and Cummins' engineers performed a detailed review of the design, build, integration and commissioning of the Hydrogenics Advanced Fuel Cell Bus and implemented a series of upgrades to improve the safety, performance and reliability of the bus before the real-world demonstration with SunLine.

Hydrogen Fueling System Upgrades

Issues with components of the hydrogen fueling system required replacement of parts and rework. Due to a manufacturer product recall, the thermally activated pressure release device ports installed on the hydrogen lines had to be replaced. Hydrogen pressure release device ports allow for hydrogen in the storage tanks to be safely released in the atmosphere in case of an emergency (Figure 33).

Figure 13: Hydrogen Pressure Release Device Ports Locations



Source: NFI Group Inc.

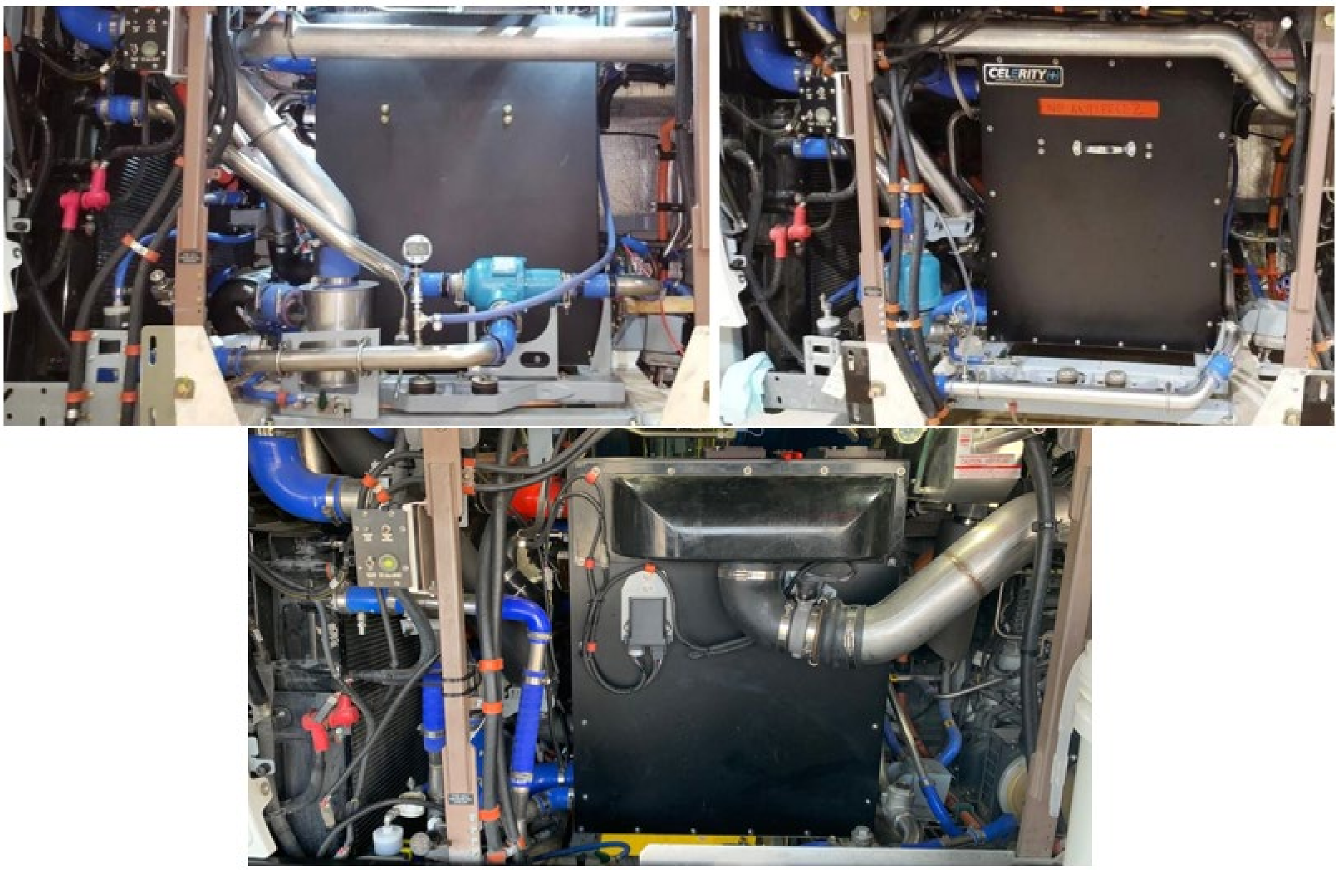
New Flyer determined that the hydrogen tanks installed on the bus had to be replaced as the selected tank model failed to pass accelerated lifecycle testing. A new hydrogen tank model was selected but because of its larger diameter, a new hydrogen tank rack had to be designed. The new hydrogen tanks were installed in May 2018.

Fuel Cell Temperature Control Improvements

In early 2018, issues with the fuel cell cooling were identified. Difficulty providing and maintaining correct coolant operating temperature setpoints in hot weather and low humidity conditions typically experienced in Palm Springs, CA led to limited maximum output power of the Celerity fuel cell power system (around 30 kW instead of 60 kW). Several improvements to the fuel cell module ventilation and cooling system were performed to mitigate performance and reliability issues. The improvements consisted of the following:

- Instrumented the fuel cell cooling system to better understand its cooling capacity, the heat rejection of the fuel cell and better predict the fuel cell limiting ambient temperature.
- Modified the fuel cell module ventilation and exhaust ports to mitigate fuel cell module enclosure overheating problems (Figure 34).

Figure 3414: Different Iterations of Fuel Cell Cooling and Ventilation System



Source: NFI Group Inc.

- Upgraded the fuel cell module ventilation plumbing to standard silicone hoses and automotive grade piping to help overcome overheating issue of the internal fuel cell components.
- Removed the three-way valve and installed a double deionization filter assembly to improve coolant flow and increase capacity to maintain coolant ionization levels.
- Installed a new rear engine door to increase air flow in the engine compartment to help cool down the fuel cell.
- Upgraded the fuel cell ventilation filter to keep dust out of the fuel cell electronics.
- Improved the radiator cooling fans control algorithm to better meet coolant temperature set points.

- Changed fuel cell cooling system coolant.

Celerity Fuel Cell System Improvements

Celerity Plus is a prototype fuel cell module that was designed in 2014 and it has not been pushed toward commercialization, Hydrogenics focusing instead on commercializing its HyPM® fuel cell product line. As a result, the Celerity Plus on the Hydrogenics Advanced Fuel Cell Bus is a prototype that hasn't been developed to meet the reliability and serviceability requirements of real-world transit operation. Because it is a prototype, the Celerity Plus fuel cell power system had to be removed from the bus on several occasions for diagnostic and minor repairs and had to be shipped to Hydrogenics in Canada for major repairs. Several improvements to the Celerity Plus fuel cell power system were performed to mitigate performance and reliability issues. The improvements consisted of the following:

- Modified the fuel cell air delivery system to improve fuel cell temperature control (see previous section).
- Modified accessibility of the fuel cell to improve serviceability (see Figure 35).
- Improved the fuel cell diagnostics and fault codes reporting to improve serviceability.
- Changed the fuel cell air blower, recirculation pump and controller parts to improve reliability.
- Rebuilt fuel cell stacks to improve performance.
- Regularly replaced deionization filters and coolant to avoid contamination issues causing high voltage isolation faults.
- Replaced Celerity Plus fuel cell power systems having experienced operating conditions impacting the health of the fuel cell, such as long duration of continuous low power operation, suboptimal coolant temperature control and control software calibration issues.

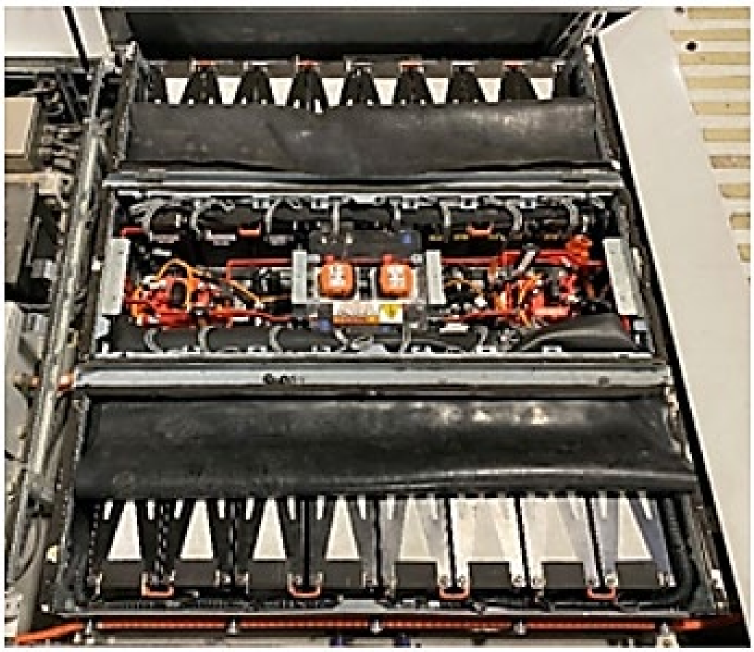
Figure 35: New Fuel Cell Delivered to New Flyer Facility and Installed on the Bus

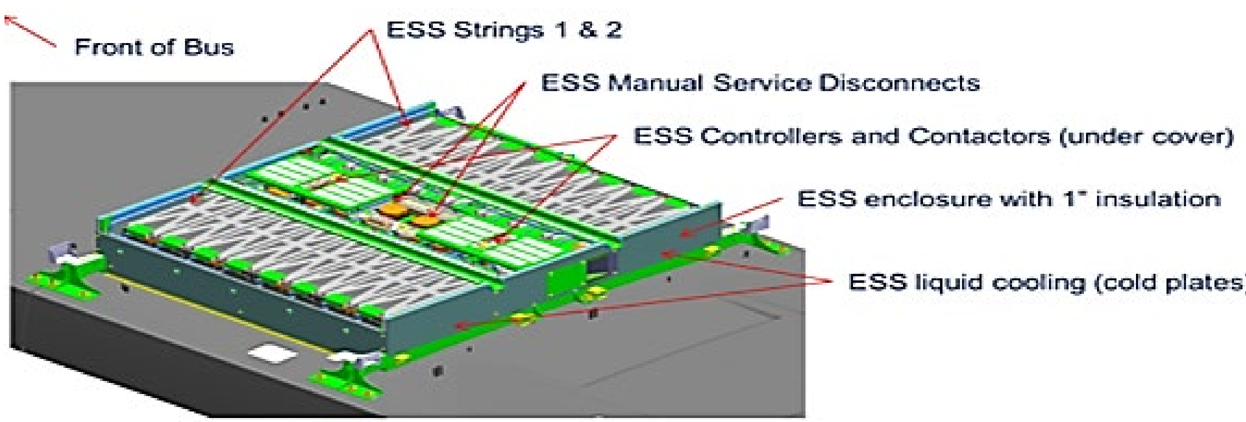
Source: Cummins Inc.

High Voltage Battery Refurbishment

The New Flyer XHE40 bus platform on which the Hydrogenics Advanced Fuel Cell Bus was built on was manufactured in 2016. Due to project delays, the bus experienced limited use until late 2019 and several related issues with the high voltage batteries were observed. In addition, the New Flyer XHE40 bus platform for this project uses battery modules from A123 Systems that have been discontinued, are not being supported and are no longer in use in New Flyer's battery electric and fuel cell electric bus product lines (Figure 36). This introduced issues to get product support and new battery module for replacement from A123 Systems.

Figure 36: Roof-Mounted Battery Energy Storage System with A123 Battery Modules





Source: NFI Group Inc.

The high voltage battery refurbishment consisted of replacing nine (out of 16) battery modules that showed low state of health, replacing the wire harness for the battery string two, retorquing the battery terminal connections, charging, balancing and commissioning the battery pack (battery strings one and two), load testing battery strings one and two, and verifying the state of health of the battery modules by repeating several charge/discharge cycles.

Integration of Additional Inductor and Low Voltage DC/DC Converter

An additional fuel cell inductor was integrated to reduce overheating issues and power electronics and fuel cell module performance derating in high ambient temperature conditions. An additional hybrid beltless alternator (low voltage DC/DC converter) was also integrated to help maintain voltage in the 24 Volt batteries during the summer months when the demand on the low voltage system from the radiator fans can be high.

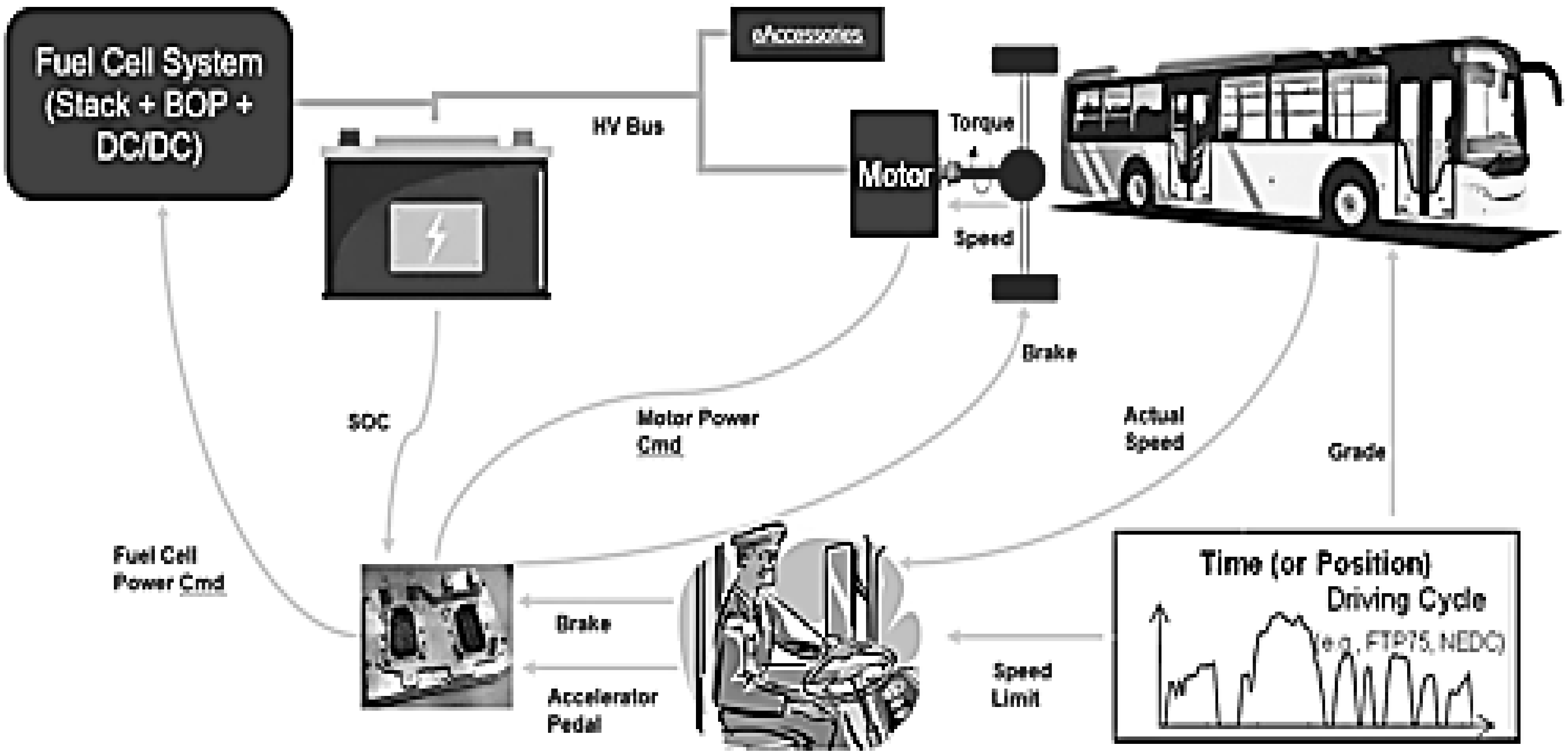
Installation of Data Acquisition System

A cloud-based data logger was installed on the Hydrogenics Advanced Fuel Cell Bus to remotely monitor system performance during testing and validation as well as the demonstration with SunLine. The new data acquisition system also enabled faster service and maintenance by providing remote diagnosis capabilities to the Cummins service team.

Vehicle Performance Simulation

A closed-loop simulation model was created to simulate the operation of the fuel cell electric powertrain, understand its operating profile and calibrate the control system for better performance (Figure 37).

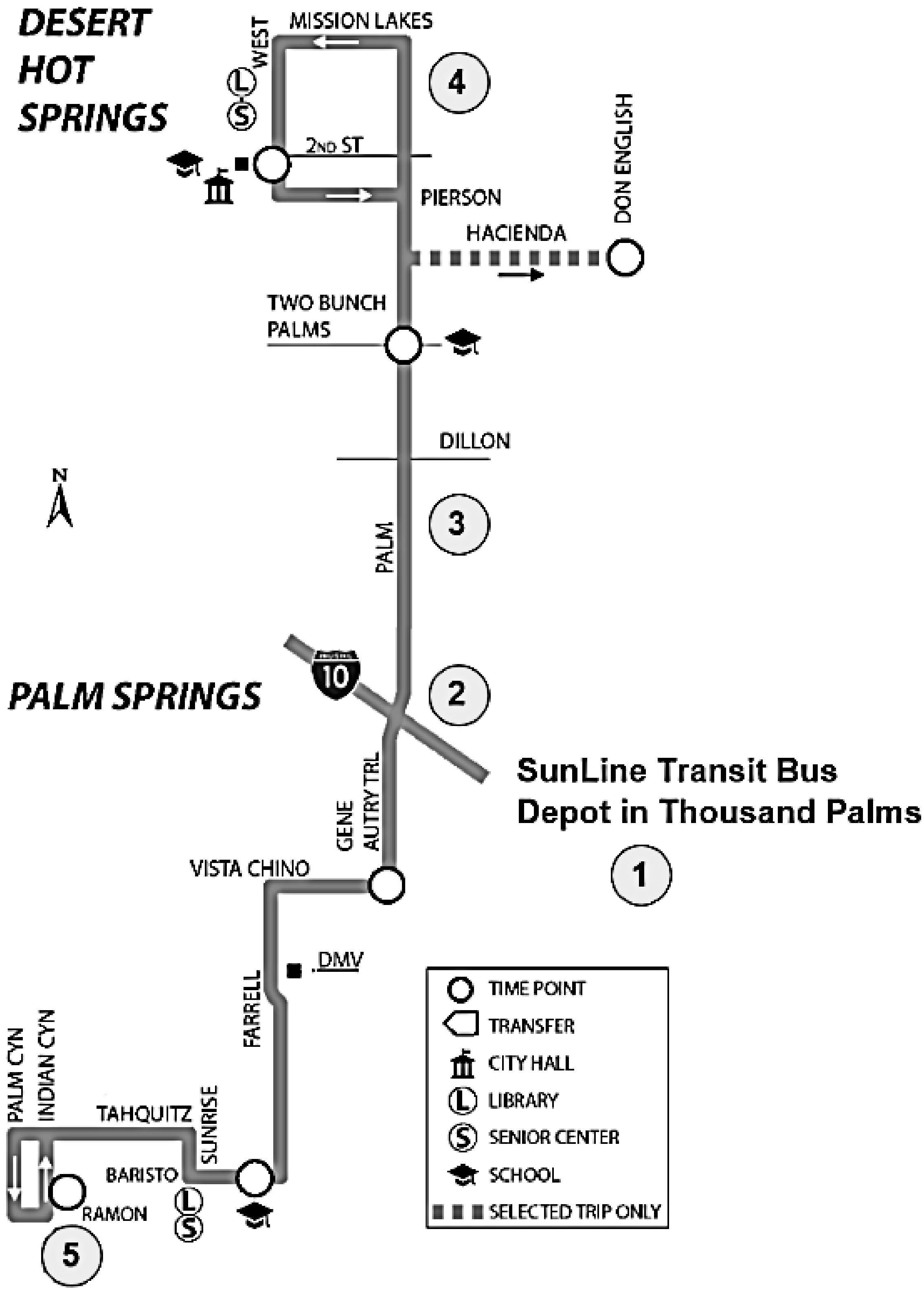
Figure 37: Fuel Cell Bus Powertrain Simulation Model High-Level Architecture



Source: Cummins Inc.

The model was used on standard drive cycles and route data from actual SunLine bus routes, such as Route 14 (Figure 38).

Figure 38: SunLine Route 14 and Waypoints



Source: SunLine Transit Agency

Detailed analysis for the simulation results have provided deep insights on possible improvements to the powertrain control strategy to achieve better performance on Route 14, one of the most challenging routes for SunLine. As a result, several changes to the powertrain control strategy were implemented on the Hydrogenics Advanced Fuel Cell Bus.

The vehicle performance simulation also revealed that the fuel cell module that had been selected for this project is undersized for transit bus applications in suburban and rural areas. SunLine presents several bus routes were the fuel cell module, even when operating at its peak 60 kW power, struggles to charge sustain the high voltage battery pack. Using the vehicle performance simulation model, the New Flyer and Cummins engineers were able to adapt the powertrain control strategy to provide better performance on power-intensive bus routes using the fuel cell module for longer hours, at higher average output power and consuming more hydrogen fuel. This new powertrain control strategy was expected to allow for the Hydrogenics Advanced Fuel Cell Bus to operate on all the SunLine bus routes.

Vehicle Testing and Validation

After the successful completion of the commissioning of the Hydrogenics Advanced Fuel Cell Bus, the bus was driven for about 50 miles in low power operation around New Flyer's facility in Ontario, CA. Additional tests were completed on the traction motor to obtain the clearance from Siemens to release the bus for on-road operation. The bus was then moved to Palm Springs, CA where vehicle testing, and validation activities were performed prior to delivery of the bus to SunLine. About 1,000 miles were driven following the test plan below:

- Powertrain control system calibration and tuning: the objective was to fine tune the control system to allow for an optimal power allocation between the fuel cell module and the high voltage battery and to measure the time to charge up the high voltage battery with the fuel cell with the cabin heating, ventilation, and air conditioning and other accessory loads on during vehicle idle. This was done through stationary load tests on the fuel cell module (10, 30, 50, and 60 kW fuel cell output power) and on several SunLine's bus routes.
- Fuel cell radiator control system calibration and tuning: the objective was to verify that radiator fan speed is controlled and well-tuned and measure the time for the coolant to reach its set point temperature through stationary load tests on the fuel cell module (10, 30, 50, and 60 kW fuel cell output power) and on several SunLine's bus routes.
- Fuel cell cooling system testing: the objective was to evaluate the performance of the fuel cell cooling system and measure its maximum ambient temperature operating condition through stationary load tests on the fuel cell module (10, 30, 50, and 60 kW fuel cell output power) and on SunLine's bus routes.
- Powertrain system verification: the objective was to perform low and high fuel cell power testing to confirm that the powertrain can operate without faults or issues and to verify that the different subsystems are behaving as expected in real-world operating conditions. Low power testing was carried out on a parking lot and through stationary

load tests on the fuel cell module. High power testing was carried out on several SunLine's bus routes.

- Traction motor validation testing: The objective was to cover 500+ miles without issues or faults to confirm proper powertrain system operation and complete the final traction motor validation testing (Siemens M4), necessary to release the bus to SunLine for the one-year demonstration.

Testing validated the successful resolution of the issues observed during commissioning with the vehicle upgrades described in pages 31 to 36. The refurbished high voltage battery performed as expected and the fuel cell system with its new fuel cell module, improved temperature control and upgraded power electronics was able to reach peak power without overheating and during longer durations. No high voltage isolation was observed, and the bus was able to complete several SunLine bus routes with the new powertrain configuration and the new control system at ambient temperatures below 100°F (Figure 39).

Figure 39: On-Road Testing Summary of the Hydrogenics Advanced Fuel Cell Bus

Day	Route	Distance	Max Ambient	SOC Start	SOC End	Avg FC Power	Faults	STATUS
[-]	[-]	[miles]	[F (C)]	[%]	[%]	[kW]	[-]	[-]
9-Oct	Route 14	62	95 (35)	85%	70%	53	0	PASS
12-Oct	Route 14	62	105 (41)	82%	50%	50	1	FAULT
6-Nov	Route 14	62	91 (33)	82%	55%	52	0	PASS
1-Dec	Route 32	77	81 (27)	80%	72%	45	0	PASS
2-Dec	Route 111	76	85 (29)	78%	71%	50	0	PASS
2-Dec	Route 111	76	86 (30)	76%	68%	42	0	PASS
3-Dec	Route 111	71	85 (29)	61%	70%	45	0	PASS
3-Dec	Route 111	71	77 (25)	80%	77%	32	0	PASS
4-Dec	Route 111	70	83 (28)	78%	69%	40	0	PASS
4-Dec	Route 14	70	81 (27)	78%	73%	48	0	PASS
7-Dec	Route 20	70	79 (26)	65%	53%	50	0	PASS
7-Dec	Route 21	50	79 (26)	63%	70%	45	0	PASS

Source: Cummins Inc.

When the ambient temperature is higher than 100°F (38°C), the bus was not able to complete the challenging Route 14. The high temperature and low humidity conditions experienced in Palm Springs during the summer and fall months require a lower fuel cell module coolant inlet temperature than what the fuel cell cooling system was designed for. Under extreme conditions, the fuel cell module is unable to operate at peak power. Despite several improvements to the fuel cell cooling system, it was determined that operating constraints during the summer and fall months were likely to be experienced by SunLine.

Noise Testing

Noise testing was conducted on the Hydrogenics Advanced Fuel Cell Bus to determine if the bus acoustic noise levels met the bus procurement standards from the American Public Transportation Association.[1] Testing was completed following the New Flyer Vehicle Noise Test Procedure (PN 370827/B), and instrumentation was installed in compliance with SAE Standard J366. The American Public Transportation Association procurement guidelines specify that:

1. The bus generated interior noise level shall not exceed 80 A-weighted decibels at seat location in the passenger area and driver shall not experience noise level of more than 75 A-weighted decibels.
2. The bus generated exterior noise level shall not exceed 80 A-weighted decibels under full power acceleration when operated at zero to 35 mph at curb weight.
3. The maximum exterior noise level generated by the bus pulling away from a stop at full power shall not exceed 83 A-weighted decibels.
4. The bus generated noise at curb idle shall not exceed 65 A-weighted decibels.
5. If an audible discrete frequency is detected, a penalty of five A-weighted decibels shall be added to the sound level measured.

According to the SAE J366 Standard, LAFmax, the maximum Sound Level with 'A' Frequency weighting and Fast Time weighting during the measurement period, was used as a parameter to evaluate the interior and exterior noise level of the bus. LAFmax measured during testing can be seen in Figure 40 and Figure 41 below.

1 Standard Bus Procurement Request for Proposal. APTA. 2013. https://www.apta.com/research-technical-resources/standards/procurement/apta-bts-bpg-gl-001-13/

Figure 40: Hydrogenics Advanced Fuel Cell Bus Interior Noise Testing Results

	Accessories ON		Accessories OFF	
	Driver Seat	Rear Passenger Bench	Driver Seat	Rear Passenger Bench
35 MPH Test	74 dBA	76 dBA	74 dBA	77 dBA
APTA Noise Spec.	75 dBA	80 dBA	75 dBA	80 dBA

Source: NFI Group Inc.

The interior noise levels on the Hydrogenics Advanced Fuel Cell Bus were lower than the American Public Transportation Association noise specifications when measured at the driver seat and the rear passenger seat bench.

Figure 41: Hydrogenics Advanced Fuel Cell Bus Exterior Noise Testing Results

	Drive By Test	Pull Away Test	Curb Idle Test
Measured Sound Level	73 dBA	68 dBA	55 dBA
Adjusted Sound Level	78 dBA	68 dBA	55 dBA
APTA Noise Spec.	80 dBA	83 dBA	65 dBA

Source: NFI Group Inc.

The exterior noise levels on the Hydrogenics Advanced Fuel Cell Bus were lower than the American Public Transportation Association noise specifications when measured during the drive by test, pull away test and curb idle test.

Fuel Economy Evaluation

Testing was conducted on the Hydrogenics Advanced Fuel Cell Bus to evaluate the fuel economy and energy consumption on the Transit Coach Operating Duty Cycle also referred to as Business-Arterial-Commuter duty cycle. Energy consumption and fuel economy were measured at three separate vehicle weight conditions: 1) curb weight, seater load weigh and gross vehicle weight. Energy consumption and fuel economy was measured by New Flyer on local test routes using onboard sensor equipment.

Energy consumption results can be seen in Figure 42. This table indicates the overall energy consumption of all subsystems, minus the energy returned to the system from the fuel cell.

Figure 42: Hydrogenics Advanced Fuel Cell Bus Energy Consumption Results

	Energy Consumption (kWh/mile)		
	CW	SLW	GVW
Central Business District Segment	2.06	2.54	2.69
Arterial Segment	2.36	2.43	2.54
Commuter Segment	1.88	1.91	1.95
Business-Arterial-Commuter Drive Cycle	2.10	2.32	2.40

Source: NFI Group Inc.

Fuel economy results can be seen in Figure 43.

Figure 43: Hydrogenics Advanced Fuel Cell Bus Fuel Economy Results

	Fuel Economy (miles/kg)		
	CW	SLW	GVW
Central Business District Segment	5.21	4.98	4.46
Arterial Segment	6.00	5.15	5.07
Commuter Segment	6.91	6.94	6.32
Business-Arterial-Commuter Drive Cycle	5.87	5.50	5.07

Source: NFI Group Inc.

CHAPTER 4: Fuel Cell Bus Demonstration

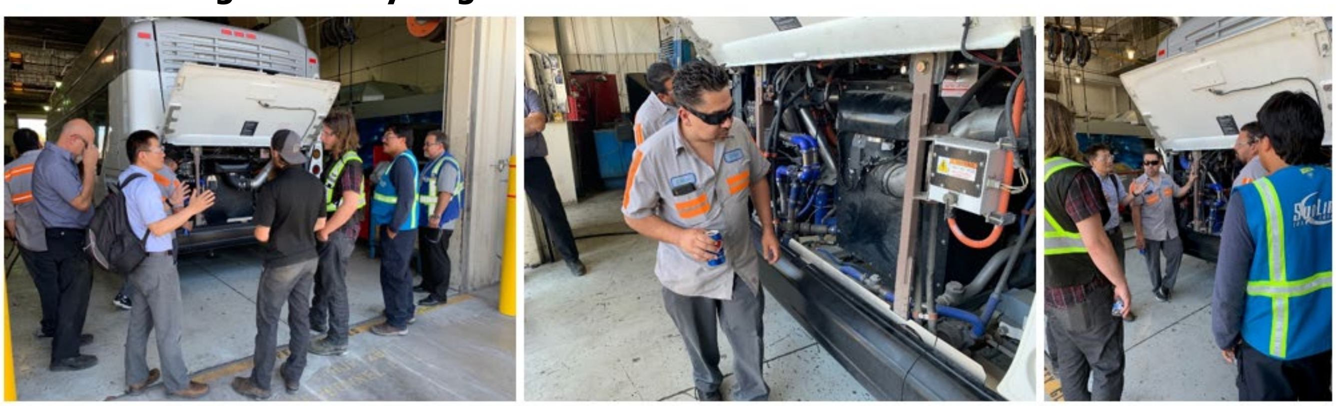
SunLine Transit Agency Staff Training

On June 12, 2019, Hydrogenics conducted training for SunLine's bus drivers and maintenance staff in order to present the Hydrogenics Advanced Fuel Cell Bus, explain its functioning and answer questions. The training was hosted by SunLine at the West Coast Center of Excellence in Zero Emission Technology. Attendees included representatives from New Flyer field service support team, Sunline maintenance mechanics and Sunline bus drivers. Figure 44 and Figure 45 show photos of the training session and bus walk around.

Figure 44: Hydrogenics Advanced Fuel Cell Bus Training at SunLine Transit

Source: Cummins Inc.

Figure 45: Hydrogenics Advanced Fuel Cell Bus Walk Around

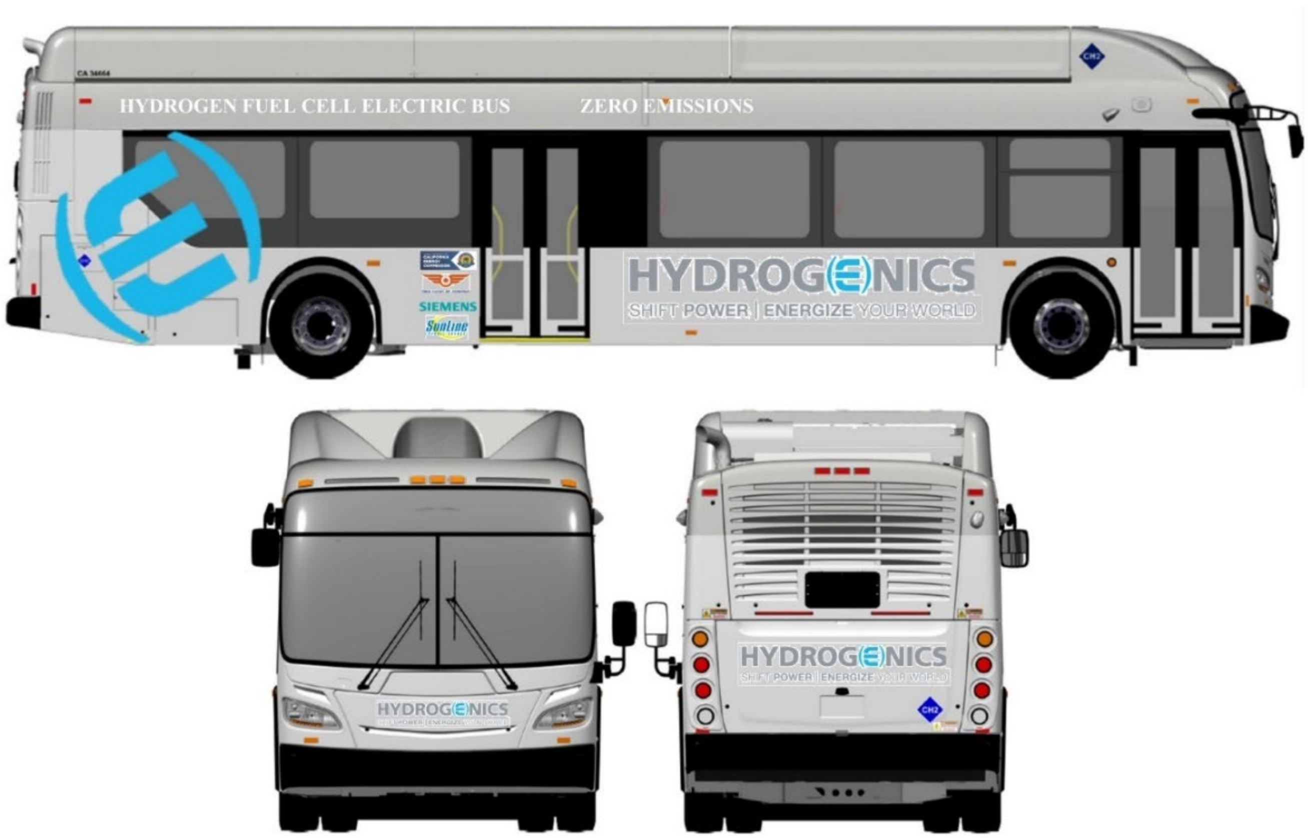


Source: Cummins Inc.

Fuel Cell Bus Authorization and Release

Before the Hydrogenics Advanced Fuel Cell Bus could be put in revenue service, it had to complete the pre-delivery inspection as the final check to ensure that the vehicle met SunLine's safety and performance requirements. The Hydrogenics Advanced Fuel Cell Bus was shipped to SunLine in May 2019 and upfitted with decals (Figure 46) and transit bus auxiliary equipment necessary for revenue operation such as fare box, camera and audio systems, radio, and New Flyer Connect telematics system.

Figure 46: Hydrogenics Advanced Fuel Cell Bus Decals



Source: Cummins Inc.

The preliminary bus inspection (Figure 47) in June 2019 revealed several issues needing to be fixed and areas needing improvement before the pre-delivery inspection could proceed further. These issues and areas for improvements are described in Chapter 3, pages 31 to 36.

Figure 47: Hydrogenics Advanced Fuel Cell Bus Preliminary Bus Inspection

Source: Cummins Inc.

Upon resolution of the issues and areas for improvements mentioned above, SunLine registered the Hydrogenics Advanced Fuel Cell Bus with the California Department of Motor Vehicles in November 2020 and permanent exempt license plates were installed on the bus. The bus was then re-delivered to SunLine in late December 2020 and went through the pre-delivery inspection in early 2021 (Figure 48).

Figure 48: Hydrogenics Advanced Fuel Cell Bus Pre-Delivery Inspection

Source: Cummins Inc.

After minor issues were fixed, the bus completed the pre-delivery inspection and successfully completed the final testing by SunLine where the bus was operated on a "ghost" route, mimicking transit bus operation for an entire day. The Hydrogenics Advanced Fuel Cell Bus was authorized and released for transit operation by SunLine in March 2021 (Figure 49).

Figure 49: Hydrogenics Advanced Fuel Cell Bus Ready for Transit Operation

Source: Cummins Inc.

Fuel Cell Bus Demonstration Results

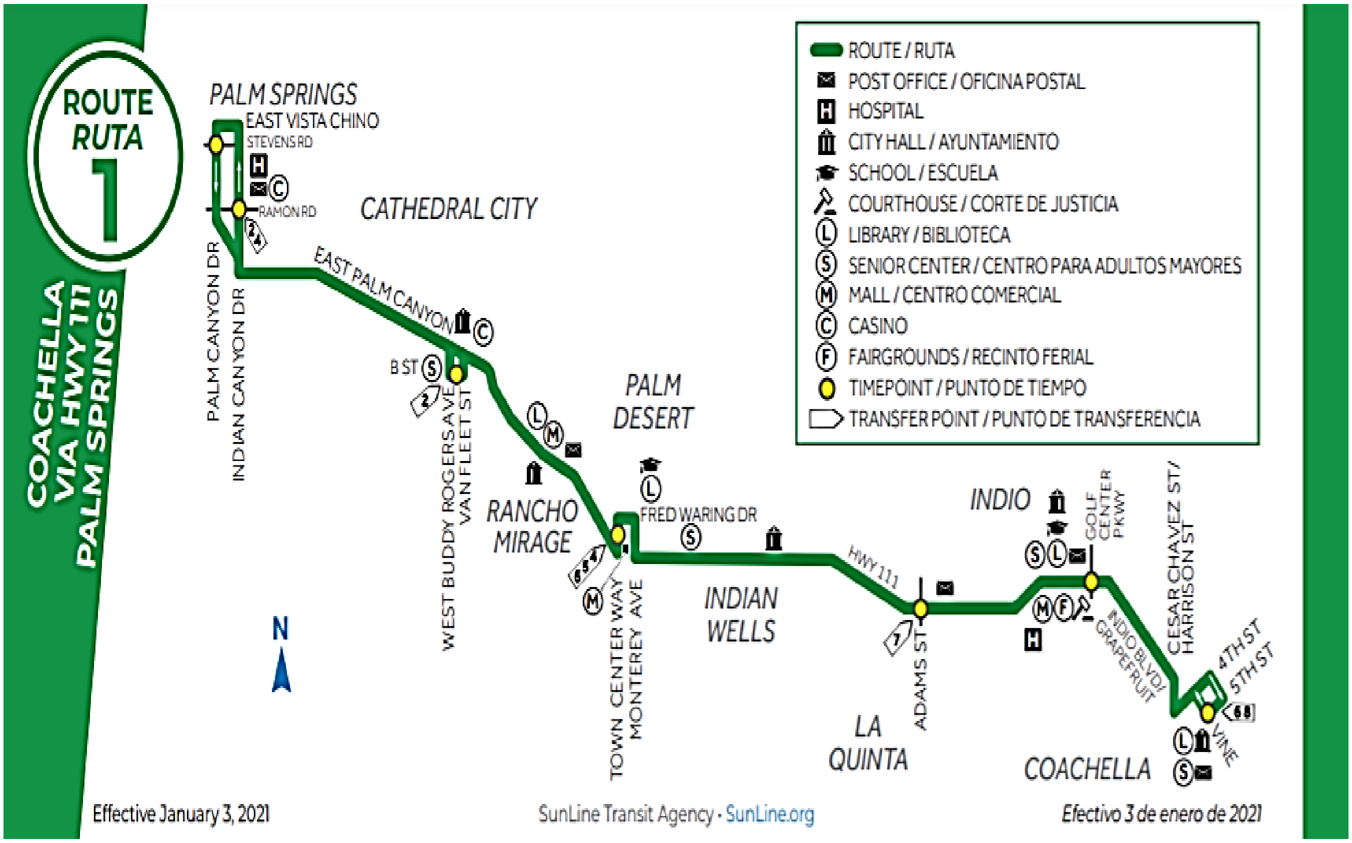
The field demonstration of the Hydrogenics Advanced Fuel Cell Bus began on March 12, 2021 at SunLine. SunLine provides safe and environmentally conscious public transportation services and alternative fuel solutions to meet the mobility needs of the Coachella Valley. SunLine service includes local fixed route buses, a bus circular loop, commuter/express buses, micro transit, and paratransit buses. In total, the service area covers 1,120 square miles over 15 local bus routes, one commuter/express bus between Indio and San Bernardino, and paratransit services for people who are unable to use fixed route buses.[2] SunLine's current fixed route fleet is made up of 59 Compressed Natural Gas buses, 16 hydrogen fuel cell buses and four battery electric buses.[3] SunLine selected Route 1 to demonstrate the Hydrogenics Advanced Fuel Cell Bus. Route 1 operates all week from 5 am to 11 pm between downtown Palm Springs and downtown Coachella, about 30 miles away (Figure 50).

2 SunLine Transit Agency Zero-Emission Bus Rollout Plan. 2020.

https://www.sunline.org/sites/default/files/SunLine%20ZEB%20Rollout%20Plan_FINAL.pdf

3 SunLine Transit Agency https://sunline.org/

Figure 50: SunLine Transit Agency Route 1 Map



Source: SunLine Transit Agency

New Flyer and Cummins provided continued local service engineering support during the demonstration. Fuel cell module service and repairs were carried out by Cummins trained technicians based out of Bloomington, CA. Operational data was collected during the demonstration and analyzed. The summary of the data collected during the fuel cell bus demonstration and a comparison with Compressed Natural Gas bus performance data at SunLine is presented in Table 1 and Table 2. [4]

Table 1: Hydrogenics Advanced Fuel Cell Bus Demonstration Summary Results

	Hydrogenics Advanced Fuel Cell Bus	COMPRESSED NATURAL GAS
Number of buses	1	5
Data period	03/11/2021 – 05/05/2021	01/2017 – 07/2019
Total mileage in data period	2,236	813,575

4 L. Eudy and M. Jeffers. April 2020. SunLine Transit Agency American Fuel Cell Bus Progress Report, Data Period Focus: January 2017–July 2019. https://www.nrel.gov/docs/fy20osti/71312.pdf

	Hydrogenics Advanced Fuel Cell Bus	COMPRESSED NATURAL GAS
Total fuel cell power plant hours	130	-
Fuel economy (FCEB mi/kg or COMPRESSED NATURAL GAS mpgge)	6.08	3.44
Fuel economy (mpdge)	6.87	3.85
Average speed	12.1	17.2

Source: Cummins Inc.

Table 2: Hydrogenics Advanced Fuel Cell Bus Demonstration Detailed Results

	March 2021	April 2021	*1-year Demonstration*[5]
Data period	3/11/2021 – 3/31/2021	4/01/2021 – 4/30/2021	12 months
Total mileage in data period	998	1109	27,885
Total fuel cell power plant hours	60	71	1,614
Fuel economy (fceb mi/kg or compressed natural gas mpgge)	6.40	5.23	6.08
Fuel economy (mpdge)	7.23	5.91	6.87
Average speed	12.8	11.8	12.1
Compressed natural gas fuel displaced	290	322	8,106
Greenhouse gas reduced (metric tons co_{2e})	2.5	2.7	68.8

Source: Cummins Inc.

The Hydrogenics Advanced Fuel Cell Bus performed successfully during the demonstration period, operating at speeds of up to 65 MPH in ambient temperatures ranging from 6°C to 47°C. It drove a maximum of 161.3 miles in a day and the Celerity Plus fuel cell power system was able to extend the range of the bus, providing average fuel cell power of about 30 kW.

During the demonstration, Cummins evaluated the operating limitations of the bus using the cloud-based data acquisition system to monitor the daily performance of the fuel cell module as ambient temperature increased. As expected, under the high temperature and low humidity conditions experienced in Palm Springs during the summer and fall months, the Celerity Plus fuel cell became unable to operate at peak power. As described in Chapter 3, pages 24 to 27, the fuel cell cooling system was not designed to supply a low enough fuel cell module coolant inlet temperature. While the fuel cell cooling system was originally designed for a limiting ambient temperature of about 51°C, real-world testing showed the limiting ambient temperature at which the fuel cell could operate at around below 40°C. This was caused by

5 Data extrapolated from March and April 2021 performance. Average of 143 miles/day, 8.28 fuel cell hours/day, 5 days/week. Prototype bus availability of 75%.

localized overheating issues inside the fuel cell enclosure. The Celerity Plus fuel cell power system was originally designed in 2014 and was ultimately not selected to go in production, Hydrogenics focusing its engineering and manufacturing efforts on the HD product line instead. As a result, the Celerity Plus fuel cell power system remained a prototype and the issues limiting operating ambient temperature were not resolved. In addition, upgrading the fuel cell cooling system was also not deemed a viable option as it would have required significant rework.

In May 2021, Cummins and New Flyer decided to end the bus demonstration and explore future opportunities outside of this project using Cummins' latest fuel cell products instead.

CHAPTER 5: Conclusion

Project Success

Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology purposely designed and developed for transit buses. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a transit bus (Figure 51). Funding from the CEC was a critical enabler to the overall success of Hydrogenics. By selecting Hydrogenics, the CEC grant review process provided a valuable third-party evaluation of its business model for Cummins' due diligence prior to its acquisition of the company in 2019.

Figure 51: The Hydrogenics Advanced Fuel Cell Bus

Source: Cummins Inc.

The Hydrogenics Advanced Fuel Cell Bus successfully operated on several transit bus routes, including SunLine's most challenging route: Route 14. The Hydrogenics Advanced Fuel Cell Bus represents a meaningful step in the hydrogen fuel cell industry. For Cummins, it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Lessons Learned

Throughout the duration of this project, Hydrogenics and Cummins learned valuable lessons that we believe can be helpful for the CEC or companies supporting the hydrogen and fuel cell market.

1) *Current fuel cell system design is not optimized for challenging duty cycles.*

The current fuel cell power system, with its 60-kW maximum power, is not optimized for transit bus applications in suburban and rural areas and for high temperature and low humidity operation. In these conditions, it cannot provide sufficient power, torque and energy to support a 40-ft. transit bus throughout its daily duty cycle and prolong the life of the battery by operating in a charge sustaining mode.

2) *Current system design is not well-suited for commercialization.*

The current powertrain architecture and design is a prototype that will not be commercialized and cannot be easily supported in the field. In particular, it uses many prototype components that cannot be easily repaired or replaced due to prototype parts availability and product obsolescence.

3) *Current system design is not well-suited for mass market penetration.*

The current powertrain architecture and design is a prototype that is not suited to accelerate the mass market penetration of advanced zero emission fuel cell drive system technology in a transit bus. In particular, it uses many prototype components that are not commercial off-the-shelf. For instance, the Celerity Plus 60 kW fuel cell module is a prototype whose production has been discontinued.

4) *State is lacking hydrogen fueling infrastructure.*

Hydrogen fueling infrastructure, and especially infrastructure for medium and heavy-duty vehicles, remains wholly inadequate in California to support the commercialization of hydrogen fuel cell propulsion technologies. In addition, the availability of hydrogen at the existing hydrogen fueling stations is unreliable and remains a major concern for companies looking at converting their transit bus fleets to zero-emissions vehicles.

Next Steps

Going forward, Cummins is involved in several projects pursuing its most up-to-date heavy-duty fuel cell powertrain architecture and design which incorporates the key learnings from this project and leapfrogs incremental design improvements on a powertrain architecture and design originally developed in 2015. Cummins' latest generation architecture and design bring forward a state-of-the-art fuel cell powertrain that 1) is customized, tested, and optimized for transit bus applications, 2) can demonstrate the market viability of advanced zero emission fuel cell drive system technology in a transit bus, and 3) accelerates the mass market penetration of heavy-duty hydrogen fuel cell buses.

GLOSSARY

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

DIRECT CURRENT (DC)—Electricity that flows continuously in the same direction.

HYDROGENICS CORPORATION (Hydrogenics)—A company that designs and manufactures hydrogen generation, energy storage, and fuel cell products.2

HYDROGENICS USA, Inc. (Hydrogenics USA)—Hydrogenics USA was the U.S. business entity of Hydrogenics Corporation.

KILOWATT (kW)—One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.