Alberta Rail Terminal Decarbonization

Project ID: IT0162469

Name	Date	Role
Veronika Kowalczyk	August 8th, 2025	Contributor/Reviewer
Matthew Findlay	August 8th, 2025	Contributor/Reviewer
Jeff Coates	August 8th, 2025	Contributor/Reviewer
David Huck	August 8th, 2025	Contributor/Reviewer
Kyle Mulligan	August 15th, 2025	Author

Table of Contents

TABLE OF FIGURES 2

TABLE OF TABLES 5

1.0 - INTRODUCTION 6

2.0 – DIESEL ELECTRIC AND ZERO-EMISSION LOCOMOTIVES 7

- 2.1 – HYBRID DIESEL-ELECTRIC LOCOMOTIVES 7
- 2.2 – BATTERY-ELECTRIC LOCOMOTIVES 8
- 2.3 – DIESEL BATTERY-ELECTRIC LOCOMOTIVES 12
- 2.4 – FUEL CELL BATTERY HYBRID ELECTRIC LOCOMOTIVES 13
- 2.5 – LOW VERSUS HIGH HORSEPOWER LOCOMOTIVES 17
- 2.6 – LOCOMOTIVE MODERNIZATION 18

3.0 – FUEL CELL BATTERY HYBRID LOCOMOTIVE DEVELOPMENT 19

- 3.1 – CP 1002 LOW HORSEPOWER LOCOMOTIVE DESIGN AND BUILD 20
  - *3.1.1 – Duty Cycle Analysis 24*
  - *3.1.2 – Regenerative Braking 26*

4.0 – LOCOMOTIVE IN-SERVICE TESTING 26

5.0 – LOCOMOTIVE RESULTS, IMPROVEMENTS, AND NEXT STEPS 30

- 5.1 – CP 1003 AND CP 1004 FL/Y AND MTBF 30
- 5.2 – LOCOMOTIVE QUALITY IMPROVEMENTS 30
- 5.3 – NEXT STEPS 31

6.0 – HYDROGEN REFUELING INFRASTRUCTURE 31

7.0 – MECHANICAL INTEGRATION AND MAINTENANCE PROCEDURES 39

8.0 – COMMERCIAL READINESS PLANNING 39

- 8.1 – LOCOMOTIVES IN HEAVY-HAUL OPERATION 40

9.0 – TECHNOLOGY SUCCESS METRICS 42

10.0 – LESSONS LEARNED AND CHALLENGES 44

11.0 – GHG MONITORING 45

Table of Figures

Figure 1 - Illustration showing the high-level systems of a diesel-electric locomotive (a) and the locations which are replaced during the conversion process to create a hydrogen-battery fuel cell locomotive. 8

Figure 2 - Mainline designed battery-electric locomotive used within a diesel-electric hybrid consist (a) and terminal switcher battery locomotive (b) from each North American Original Equipment Manufacturers (OEMs). 9

Figure 3 - CANDO Rail Services (a) and WATCO (b) battery-electronic low horsepower switcher locomotives. 10
Figure 4 - (a) CN/Knoxville Locomotive Works low horsepower and (b) Progress Rail/Electromotive high horsepower hybrid-diesel locomotives (Photos Courtesy of Railway Age and Colorado Joint-Line). 13
Figure 5 - Illustration of the electrochemical reaction within the fuel cell stack and the production PEM fuel cell used in the locomotives. 14
Figure 6 - High-level summary of the process of using hydrogen gas to drive a locomotive electric traction motor and the overall locomotive architecture. 15
Figure 7 – (a) BNSF and (b) Sierra Northern Hydrogen Hybrid switcher locomotive (RailPicture.net photo Nathan Zachman, Trains) 15
Figure 8 - CP 1001 hydrogen fuel cell battery hybrid locomotive. North America's first for line-haul operation. 17
Figure 9 – CSX Huntington, WV, USA locomotive modernization facility. 19
Figure 10 - CPKC's CP1001 and CP1002 Low Horsepower (LHP) locomotives shown in images (a) and (b). 20
Figure 11 - Example of the CP 1001 retrofit "kit" concept showing the pre-assembled skid for the cooling fans, radiator, and hydrogen cylinders. 21
Figure 12 - Rendering of the CP hydrogen-battery electric retrofit kit. The kit consists of two pre-assembled "skids" which are mounted to the top deck of the locomotive and a traction battery system “battery box” which is mounted in place of the orginal diesel fuel tank under the locomotive frame. Note Zero-Emission Components include Fuel Cells, Batteries, and associated Power Electrics. 22
Figure 13 - (a) Pre-made zero emission component assemblies installed on the locomotive platform as “skids” with the original locomotive body being installed over top and the completed locomotive platform (b) once final assembly has been completed. 22
Figure 14 - Main skid (a) and Rear skid (b) for the 6-Axle DC line-haul locomotive. 23
Figure 15 – Completed CP 1003 (a) and CP 1004 (b) hydrogen fuel cell battery locomotives. 23
Figure 16 - Low horsepower duty cycle analysis to determine fuel cell power demand requirements and ensure a sufficient battery State of Charge (SOC) can be maintained... 25
Figure 17 - Pre and Post-Test process for each test for the CP 1200 locomotive and tender. 27
Figure 18 - Air Products site evaluation at CPKC’s Kipp Yard terminal. 33
Figure 19 - Fixed-point refueling infrastructure site plan. 33
Figure 20 - Initial construction at site – grading, concrete foundation pouring. 34
Figure 21 - Initial construction at site – concrete pouring, electrical work, lighting post installation. 35
Figure 22 - Trenching for hydrogen supply line vault. 35
Figure 23 - Construction at Kipp Yard terminal as in August 2025 36

Figure 24 - (a) CP 1004 showing dispenser nozzle and grounding cable attached to the locomotive and photo (b) showing DTL Refueler attached to the CP 1004 at CPKC's Lethbridge "Kipp" terminal. 37
Figure 25 - L to G Refueler on-site in Lethbridge, AB. 38
Figure 26 - Fixed-Point refueling infrastructure. 39
Figure 27 - Map of the North American Class I railway networks. 41
Figure 32 - (a) Sealing of fuel cell exhaust pieps for 3 fuel cells and (b) wire mesh installed for hydrogen venting over fuel cell enclosures. 45

Table of Tables

Table 1 - Cost comparison versus CO_2 reduction between a battery-electric switcher locomotive and a hydrogen fuel cell battery hybrid switcher locomotive. Note the battery-electric switcher locomotive is currently not commercially available in North America. ... 11
Table 2 - Quantitative and Qualitative comparison table between Battery-Electric and Hydrogen-Battery locomotives. 12
Table 3 - Low horsepower CP1003 and CP 1004 locomotive testing summary. 28
Table 5 - Project defined success metrics and achievements. 42

1.0 - Introduction

This report has been created in support of the final milestone requirements for the "Alberta Rail Terminal Decarbonization" project. This project has been executed using funding awarded to the Canadian Pacific Kansas City ("**CPKC**")[1] railway company by Emissions Reduction Alberta ("**ERA**") in December 2023. This report includes details on locomotive and hydrogen infrastructure builds including evidence to support proof of completion. Project results are followed by a commercial readiness plan and detailed report on project related Greenhouse Gas emissions ("**GHG**"). Portions of this report are already included in the final report provided by CPKC to ERA as part of the Shovel Ready Challenge – The CP Hydrogen Rail Initiative. Some of these portions are similar due to synergies with some activities included in the previous project.

The funding received by ERA of $7M is incremental to CPKC's investment of approximately $17.7M for a total of $24.7M for the project. The total funding has enabled CPKC, as part of the project scope, to convert two (2) diesel-electric locomotives to operate on a combination of hydrogen fuel cells and batteries as power generating replacements for the conventional diesel engines and related components. Fuel cells output energy by combining compressed hydrogen gas and atmospheric oxygen and creating an electro-chemical reaction between these two elements within a fuel cell stack. The output electricity from the fuel cells charges onboard batteries to turn the existing electric traction motors which have been re-used from the original diesel-electric platform. In low power demand scenarios, the fuel cells act as onboard electrical generators used to recharge the batteries. In high power demand scenarios, both the fuel cells and the batteries supply electricity to produce tractive power.

Fuel cells require highly pure compressed hydrogen gas as a fuel source or feedstock. As such, the awarded funding has been used to purchase and install hydrogen refueling infrastructure in the form of on-site liquid storage, evaporation, compression, and dispensing equipment. The refueling facility storage liquid hydrogen supplied by Air Products ("**AP**") converting it to gas for dispensing and operation within the locomotives. A liquid to gas mobile refueler has also been setup on-site in order to demonstrate Direct-to-Locomotive ("**DTL**") refueling which is critical within Class I railroad operations. Initial supply of "gray" hydrogen has been used to demonstrate the operation of the locomotives in service while awaiting the completion of AP's Edmonton, AB Advanced Net-Zero Hydrogen Energy Complex designed to produce low carbon liquefied "blue" hydrogen. AP also has mobile trucking delivery capabilities of liquid hydrogen from Edmonton, AB to Lethbridge, AB.

The main project goal that this project has aimed and successfully achieved has been to deploy two converted locomotives for local service operations in the Lethbridge, AB region. Local freight revenue trains provide daily service in all directions (i.e. North, East, South, West) out of Lethbridge, AB. Destinations include servicing facilities as far as Aldersyde, AB (North), Taber, AB (East), Coutts, AB (South), and Crowsnest, AB (West). The round-trip mileage for these revenue service plans is up to 160 miles. The goal of these trains is to perform deliveries and pick ups of freight cars from individual customer facilities (ex. grain elevators). The freight cars which are picked up and transported back to Lethbridge "Kipp" terminal are assembled into freight trains for later delivery to other terminals across North America using higher horsepower mainline locomotives. These freight trains would be considered long haul trains whereas the locomotives developed within this project would be considered local operations or switch locomotives.

This report describes CPKC's success in deploying hydrogen fuel cell battery locomotives in freight revenue service operations. Currently, both locomotives and the associated refueling station remain in service in the Lethbridge, AB region and continue to be used for rail operations. This report provides results of the including details of the locomotives such as, but not limited to: overall design and build, in-service testing, and design refinements. The report also provides details of the installed fixed-point and mobile refueling infrastructure including, but not limited to: site selection, procurement, specifications, construction, commissioning, and refueling of the locomotives. A commercial readiness plan is provided in this report followed by the result of the project GHG monitoring in a separate attachment.

2.0 – Diesel Electric and Zero-Emission Locomotives

This section describes the principles of zero-emission locomotives including battery only locomotives which also exist within the industry.

2.1 – Hybrid Diesel-Electric Locomotives

North American freight locomotives are already, by design, hybridized, utilizing diesel generators to power electric traction motors, which create motion and ultimately enable the locomotive to haul freight. Wide adoption of diesel-electric locomotives across North America occurred before the 1960's and today represents the primary fuel driving the freight rail sector. The high-level systems of a conventional diesel-electric locomotive are illustrated in Figure 1 (a). By replacing these high-level systems with components, such as but not limited to fuel cells, batteries, hydrogen storage cylinders, and modern power electronics in areas shown in Figure 1 (b), a diesel-electric locomotive can be modernized or retrofit into a hydrogen fuel cell battery electric locomotive. Fuel cells and batteries provide the potential to generate low carbon electricity, which can be used to power the already existing electric traction motors. Essentially, these electric traction motors receive the required input electricity from the power generated by the fuel cells and batteries as opposed to the original diesel generator and alternator. The fact that diesel-electric locomotives are already, by design hybrids, makes them excellent candidates for conversion to operate on hydrogen. CPKC's design team can re-use the existing locomotive platform and up to 60% of the existing systems including, but not limited to the: cab, high-voltage cabinet, frame, traction motors, radiator fans, and blowers. This makes a modernization or retrofit process desirable and includes multiple environmental benefits from re-using older equipment.

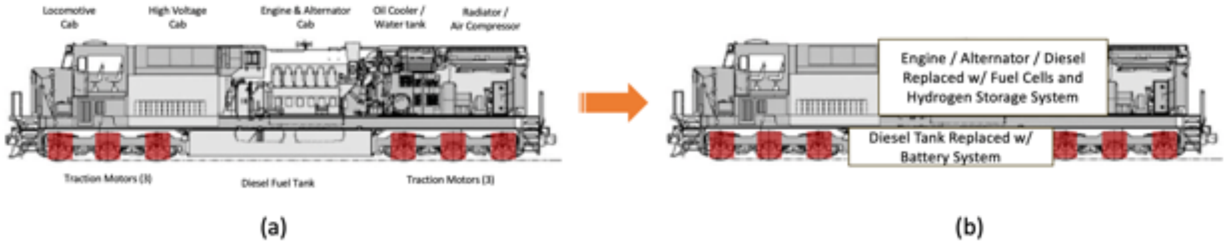

Figure 1 - Illustration showing the high-level systems of a diesel-electric locomotive (a) and the locations which are replaced during the conversion process to create a hydrogen-battery fuel cell locomotive.

The re-use process described above is known within the North American freight rail industry as locomotive "modernization." Currently, a sizeable portion of locomotive North American "modernization" occurs in the US in Muncie, IN and Fort Worth, TX. Original locomotive frame designs have been shown within the industry to be able to outlast several lifecycles of a locomotive's diesel engine. It is, therefore, common within the North American railroad industry to modernize existing locomotive platforms instead of purchasing net new locomotives. In fact, this process has become part of how current Class I railroads maintain optimal asset utilization when refurbishing their existing diesel-electric locomotive fleets. Therefore, to successfully transition locomotives within the North American freight rail industry to zero-emission, a technological solution must be capable of being incorporated into the existing locomotive modernization process versus an Original Equipment Manufacturer ("**OEM**") supplied net new locomotive and platform.

2.2 – Battery-Electric Locomotives

Currently, OEMs within North America have proposed several battery-electric locomotive designs and prototypes. Mainline versions of these locomotives which can also be used for terminal switching have been presented in two variants. The first shown in Figure 2 (a) has been designed to be operated within a mainline diesel locomotive consist[2]. The locomotive

---

[2] A locomotive consist is a set of coupled locomotives which can be placed in the head end, mid train, or tail end portions of the train. There can be several locomotive consists in a train.

provides power at cruising speeds and recovers energy on descending grades through regenerative braking. The locomotive is incapable of operating without the support of diesel locomotives for any distance with a reasonable or operationally significant tonnage, due to range and load limitations with battery technology. Therefore, the ability of battery-electric locomotives to reduce GHG emissions is limited, as diesel will always be required for mainline operation. For yard operations, the locomotive in Figure 2 (a) is not ideal due to its large size and weight. Rail terminals typically utilize lighter, lower horsepower locomotives to support operational needs but with less expensive infrastructure requirements (i.e. lighter track, wood ties, basic tie plates, spikes, etc.). The weight of the batteries increases the overall locomotive weight versus a conventional diesel-electric locomotive. The locomotive pictured in Figure 2 (b) has been designed to support terminal requirements by the second-largest locomotive OEM in North America. This locomotive remains at the prototype stage and is available for testing in California and South America. Limited information is available on this locomotive; however it is claimed to support battery capacities up to 14.5 MWh, which again would create weight conditions requiring upgraded terminal infrastructure. This locomotive's target market is mining operations where such heavy track infrastructure already exists. Some trial locomotives in Figure 2 have been delivered for limited in-service use in North America. Both battery-electric locomotives shown in Figure 2 can be recharged. Charging locations are physical and must be installed at fixed locations.

Figure 2 - Mainline designed battery-electric locomotive used within a diesel-electric hybrid consist (a) and terminal switcher battery locomotive (b) from each North American Original Equipment Manufacturers (OEMs).

Additional OEMs have designed and deployed battery-electric locomotives for smaller switching operations, typically at smaller rail terminals or customer facilities. These locomotives are smaller 4-axle versions as compared to those which have been developed by the traditional OEMs. Smaller switching operations typically require at least eight (8) hours of power per day. These operations typically have overnight downtime which enables charging to occur in preparation for the following day. Some examples of these types of battery-electric locomotives are provided in the Figure 3.

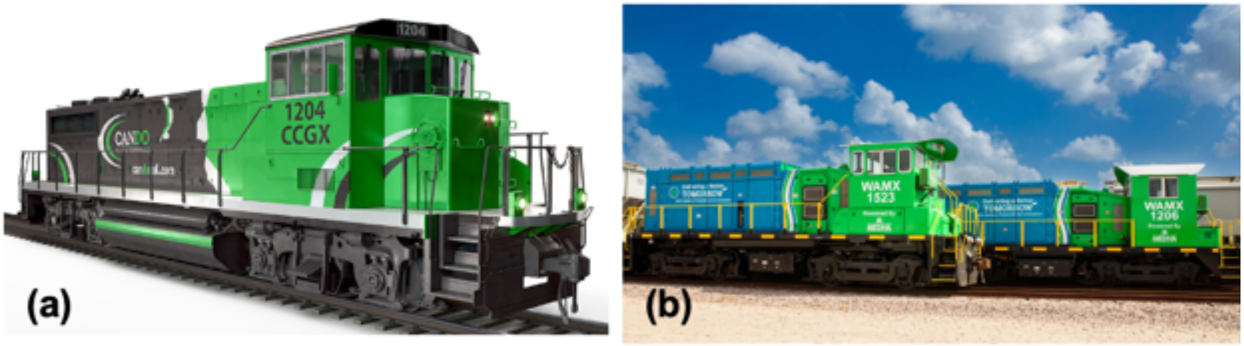

Figure 3 - CANDO Rail Services (a) and WATCO (b) battery-electronic low horsepower switcher locomotives.

Class I railroad operators who have purchased battery-electric locomotives for use in continuous daily operation will require additional locomotives to sustain operations accounting for the lengthy recharging time requirements. Therefore, for every locomotive purchased, some Class I railroads have planned to have a second locomotive on standby. This effectively doubles the required number of assets in each terminal versus today's operations with diesel-electric locomotives. Although it is feasible to utilize battery-electric locomotives within terminal operations (especially smaller operations) these locomotives cannot replicate the efficient operations established with diesel-electric locomotives within the current industry landscape. More specifically, to approach the capabilities of diesel-electric locomotives, these locomotives require fixed-point or catenary charging, up to 8-axles to support battery weight, enhanced terminal infrastructure (ex. heavier rail, concrete ties), extra assets to account for extended recharging times, and diesel-electric locomotives combined with electric-only locomotives in a hybrid consist for local switch/mainline operations or incompatible duty cycles. A comparison between the considered alternatives and the proposed solution is presented in Table 1. From the table, the total cost of mitigation for a battery-electric locomotive (including charging infrastructure is $11,959 per MT CO_2e abated. In comparison, the cost of mitigation for a hydrogen locomotive (including fueling infrastructure) is $5,322 per MT CO_2e, further demonstrating the value proposition of hydrogen technology for use in the freight rail sector. Smaller 4-axle battery-electric locomotives are more advantageous in comparison to hydrogen fuel cell battery electric locomotives if sufficiently fast recharging infrastructure can be installed however these locomotives would not be more advantageous for Class I operations mainly due to the requirement to operate 24/7 and the requirement to duplicate assets. Duplicating assets not only increases capital costs, but operating expense also soar due to increased regulatory inspections, maintenance, parts, labour, switching, and other costs.

Further quantitative and qualitative comparisons between battery-electric and hydrogen fuel cell battery electric locomotives in the Class I context are shown in Table 2. Fuel Cells provide significant advantages over battery-electric locomotives with respect to range, flexible refueling options, fueling times, and overall infrastructure costs. Both unit types are capable of equivalent levels of horsepower versus the original platforms, however a battery only locomotive is 25% heavier than using a combination of fuel cells and batteries. Therefore, battery-electric locomotives require upgraded trucks from 6-axle to 8-axle for switching and line-haul applications and ultimately require an upgraded platform thus being incapable of being manufactured as retrofit kits.

Table 1 - Cost comparison versus CO_2 reduction between a battery-electric switcher locomotive and a hydrogen fuel cell battery hybrid switcher locomotive. Note the battery-electric switcher locomotive is currently not commercially available in North America.

Battery Electric Locomotives (Low HP Switcher/Line-Haul)	
Description	**Units**
Fuel Savings vs. Diesel Switcher Locomotive Consist	100%
Average Fuel Used by Diesel Locomotives (Liters)	171,185
Estimated Capital Costs (Per BEL Locomotive)	$5,000,000
Metric Tonne Conversion (Annual)	669
Fuel Savings for 350 BEL Locomotives (Liters)	59,914,750
Estimated Total Est. Costs (Locomotives* and Charging Stations**)	$2,800,000,000
Metric Tonne Conversion (Annual)	234,115
Cost Per Metric Tonne CO_2e Saved ($CAD/MT)	$11,959

Hydrogen Locomotives (Low HP Switcher/Line-Haul)	
Description	**Units**
Fuel Savings vs. Diesel Switcher Locomotive Consist	100%
Average Fuel Used by Switcher Locomotives (Liters)	171,185
Estimated Capital Costs (Per Locomotive)	$3,560,000
Metric Tonne Conversion (Annual)	669
Fuel Savings for 350 H2 Locomotives (Liters)	59,914,750
Estimated Total Est. Costs (350 Locomotives)	$1,246,000,000
Metric Tonne Conversion (Annual)	234,115
Cost Per Metric Tonne CO2e Saved ($CAD/MT)	$ 5,322

Table 2 - Quantitative and Qualitative comparison table between Battery-Electric and Hydrogen-Battery locomotives.

Parameter	Battery-Electric Locomotive (3.6MWh)	Hydrogen-Battery Locomotive (3.6MW)
Range (% of existing diesel equivalent)	Up to 8%	Up to 30% - No Tender[3] Up to 100% - Tender (3,100 kg)
Horsepower vs. Original	Equivalent or more*	Equivalent or more*
Weight vs. Original`	543,750 lbs. (25% heavier)	435,000 lbs. (Equivalent)
Axles vs. Original	Switcher - 6 vs. 4 Line-Haul - 8 vs. 6	Switcher - 4 vs. 4 Line-Haul - 6 vs. 6
Multiple Assets Required vs. Original	Yes	No
Tender Required (Battery** or Hydrogen)	Yes	Yes
Recharge/Refuel Time	14.2 hrs.	45 mins. – No Tender 12 hrs. – Tender (3,100 kg)
Infrastructure Costs for CP Network	$675M	$170M***
Infrastructure Options	Fixed-Point	Fixed-Point Direct-To-Locomotive
Retrofit Capable	**No**	Yes

*Increased discharge rates can produce higher horsepower for short periods of time.

**Battery tenders are not commercially available. Hydrogen tenders are available commercially.

***Based on $8 per kg H_2 cost estimate.

2.3 – Diesel Battery-Electric Locomotives

Some North American Class I railroads have also invested in diesel battery-electric locomotives. These locomotives maintain the existing diesel engine or replace the existing engine with a smaller variant. The diesel engine propulsion system is supplemented with traction batteries. In lower power demand applications, the locomotives can operate on battery power for a limited time. In higher power demand applications, the diesel engine provides tractive power. Depending on the battery state of charge, tractive power may be provided by both the diesel engine and the traction batteries (i.e. blended). Regenerative braking is also available for capturing energy during dynamic braking events on downward grades. These locomotives come in both high and low horsepower variants for mainline and yard switching operations respectively. It is anticipated that these units will reduce diesel consumption by 20% - 50%. Class I railroads plan to further reduce emissions by substituting traditional diesel fuel with renewable and biodiesel fuel options. Although these locomotives can reduce emissions, they cannot practically achieve zero emission operation. Examples of these locomotives are shown in Figure 4 below.

---

[3] A tender car can be attached to a locomotive and enables additional hydrogen to be carried as fuel to extend range.

Figure 4 - (a) CN/Knoxville Locomotive Works low horsepower and (b) Progress Rail/Electromotive high horsepower hybrid-diesel locomotives (Photos Courtesy of Railway Age and Colorado Joint-Line).

2.4 – Fuel Cell Battery Hybrid Electric Locomotives

Fuel cell engines have been in development since the 1960's having one of the first applications on-board Nasa Apollo spacecraft providing electricity to recharge the onboard batteries and potable water for the astronauts. Fuel cells ingest hydrogen gas and oxygen as feedstocks. Proton Exchange Membrane ("**PEM**") fuel cells are the most common type used in the World especially in Transportation. The fuel cells are given their name due to how the hydrogen and oxygen elements are used to create electricity. In PEM fuel cells, the anode (+) and cathode (-) of the fuel cell are separated by a polymer electrolyte membrane. This membrane acts like a "screen" which only allows protons to pass or be exchanged through it. Electrons are not permitted to pass through the membrane and must take a different path to reach the cathode.

On the anode side of the stack, hydrogen atoms are broken down into ions using a platinum catalyst. The positive ions or protons are diffused across a membrane where oxygen flows into the cathode. The negative hydrogen ions or electrons flow out of the anode through a wire and into a circuit. In the case of the locomotive the overall circuit would be the main traction system bus where the electrons would have access to the traction system, traction motors, and batteries. When the electrons recombine on the cathode side of the fuel cell stack, the positive hydrogen ions and electrons combine with the oxygen to form water (H_2O) which flows out of the fuel cell. Heat is also created during the electrochemical reaction. Therefore, energy must be dispensed to ensure the fuel cells remain within a specified operating temperature. Unlike batteries, if fuel cells remain within their operating temperature, maximum power output can be sustained if there is a continuous supply of hydrogen gas and oxygen. An illustration of the fuel cell stack and the production fuel cell used in the locomotives is shown in Figure 5. The total power output of each fuel cell is 200 kW (268 HP).

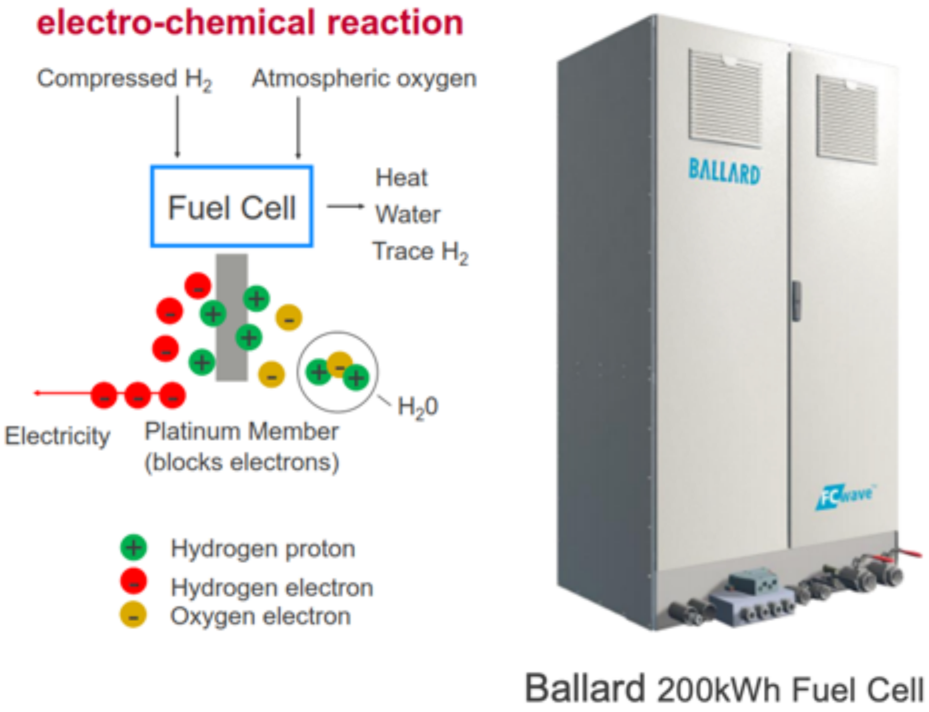

Figure 5 - Illustration of the electrochemical reaction within the fuel cell stack and the production PEM fuel cell used in the locomotives.

Due to their power output, weight, and ability to provide continuous power output, fuel cells are ideal for heavy-haul and retrofit applications. Onboard the locomotive, hydrogen gas is stored in Carbon Fibre Reinforced Polymer ("**CFRP**") pressure vessels or cylinders. Through electrically and pneumatically operated valves, hydrogen gas flows into the fuel cells through stainless steel lines. Onboard batteries are recharged by the fuel cells and act as a power buffer. Batteries respond well to transient power loads which are dependent on operator power demand needs. In high power demand situations, both the fuel cells and batteries can provide power to the traction system. Batteries are also capable of capturing power when the locomotive is using dynamic braking down grades. Power from the fuel cells and batteries are converted through advanced power electronics and delivery to the electric traction motors. All of the power delivery and communication between all components is managed through control software. A summary of the process and architecture of the locomotive is shown in Figure 6.

Figure 6 - High-level summary of the process of using hydrogen gas to drive a locomotive electric traction motor and the overall locomotive architecture.

Fuel cell prototype locomotives have been previously deployed and tested in freight applications. Development of hydrogen fuel cell powered locomotives specific to the North American freight rail industry began as early as 1999. The initial locomotive demonstrators developed for the mining industry, use a non-hybrid architecture consisting of a PEM fuel cell without the use of on-board batteries. Batteries have been incorporated in later design iterations to increase power and range while decreasing refueling times.

Deployments of mining locomotive demonstrators ultimately led into exploration of hydrogen powered freight locomotives within the North American Class I railways. The first notable project started in 2003, is a "switcher" locomotive built in collaboration between the United States (US) Department of Defense, US Department of Energy, and the Burlington Northern and Santa Fe ("**BNSF**") Railway (see Figure 7). Switcher locomotives have been selected for initial fuel cell exploration based on analysis of duty cycles from locomotive event recorder downloads. On average, the power consumption of a switcher locomotive in North American operation is 75 kW (computed over a 20-h interval) which aligns with the power output capabilities of fuel cell and battery combinations available on the market in 2003. Line-haul (road power) locomotives require up to 2.5 times more power than switcher locomotives. An important consideration when determining the feasibility of a freight locomotive hydrogen conversion is available space. Given the size versus power output of fuel cells and batteries in 2003, a line-haul locomotive conversion would not have been feasible.

Figure 7 – (a) BNSF and (b) Sierra Northern Hydrogen Hybrid switcher locomotive (RailPicture.net photo Nathan Zachman, Trains)

Advances in power output of fuel cells and batteries versus physical footprint have enabled companies such as the CPKC, to explore alternatives to Diesel fuel for powering freight line-haul locomotives. The conversion pilot initially targets locomotives which utilize DC powered traction motors. Unlike switcher locomotives, these motors require significantly higher voltages and currents which increases power management complexity. The main limiting factor in conversions due to the higher voltage and current requirements is revealed through DC-DC converters which are vital components in the power management process. As an example, off the shelf DC-DC converters are designed primarily for the automotive industry and regulate voltage on a DC-Link (or DC-Bus) limited to a maximum voltage output at 850 V and current draw of 400 A in most cases. Larger corporations which specialize in technology integration must integrate using components from other industries such as solar power in order to achieve the power requirements for line-haul locomotives.

Another reason the North American industry is exploring DC powered line-haul locomotives first is due to internal knowledge. Typically, North American locomotive vendors support locomotives under contract maintenance. These agreements significantly limit Intellectual Property (IP) sharing between the locomotive vendors and the associated Class I railroads. There is an abundance of knowledge around DC powered locomotives in both literature and in the industry, which reduces the learning curve and initial costs for performing conversions. Future partnerships with AC powered locomotive vendors may exist however as described above, there is a greater urgency being placed on the Class I railways for meeting emissions reductions targets. As such, the developments and deployments of these conversions are being driven by the Class I's and specifically in this project using funding from ERA.

In October 2020, CPKC therefore initiated a program to convert a diesel-electric locomotive, numbered CP 1001, into North America's first zero-emission hydrogen fuel cell battery electric line-haul locomotive using fuel cells and batteries to power electric traction motors. This program has the potential to significantly reduce greenhouse gas emissions from locomotive operations within Canada's transportation sector and support Canada as it aims to transition to a low-carbon future. By creating offtake demand for low carbon hydrogen, the project also supports Alberta's Hydrogen Roadmap[4] which establishes a province wide ambition to incorporate hydrogen into the regions current portfolio of energy systems.

The CPKC hydrogen fuel cell battery electric locomotive utilizes most diesel-electric locomotive components but replaces the diesel locomotive generator (engine), alternator, fuel tank, and some power electronics with zero-emission power generation components

---

[4] Alberta (2001) Alberta Hydrogen Roadmap. Retrieved from: https://open.alberta.ca/publications/alberta-hydrogen-roadmap

(i.e. fuel cells and batteries). The fuel cells require on-board hydrogen storage which includes fibre reinforced composite cylinders instead of a diesel fuel tank. The hydrogen locomotive retains all existing locomotive safety equipment and remains compliant with the *Locomotive Safety Rules* (“**LSR**”) event recorder requirements, *Locomotive Voice and Video Recorder Regulations*, and all other relevant operating regulatory requirements. By design, the hydrogen locomotive operation remains identical to current diesel-electric locomotives. The CP 1001 is shown in Figure 8.

Figure 8 - CP 1001 hydrogen fuel cell battery hybrid locomotive. North America's first for line-haul operation.

2.5 – Low versus High Horsepower Locomotives

Locomotives are commonly categorized within the freight rail industry based on horsepower. For the purposes of the hydrogen locomotive program, CPKC has two (2) categories: Low Horsepower (“**LHP**”) and High Horsepower (“**HHP**”). LHP locomotives are rated at less than 3,000 HP and typically perform switching within rail terminals or operate for relatively short distances on the mainline to service local facilities (e.g. grain elevators). Local mainline and terminal switching operation can be achieved using onboard hydrogen storage pressure vessels (i.e. cylinders) without the need to add additional hydrogen capacity.

HHP locomotives are used to power road trains that deliver freight across CPKC’s extensive North American network. HHP locomotives are rated at 4,400 HP and to achieve the required horsepower outputs, more onboard fuel cells are required on the locomotive. The locomotives also need more fuel to travel the extended distances to their destinations[5]. The locomotive does not have sufficient space to transport the additional fuel that is needed, nor are there sufficient fueling facilities en route at this time. As a result and in order to operate similar distances as diesel-electric locomotives. Although CPKC is testing HHP locomotives, significant potential for hydrogen fuel cell battery applications in Class I terminals has been identified. As such, this project has focused on further LHP development which yields significant potential as an initial decarbonization strategy for the North American freight rail industry.

2.6 – Locomotive Modernization

Locomotives are currently refurbished and upgraded in a handful specialized facilities across North America. For example, CPKC regularly sends its diesel locomotives to Texas for modernization work. Modernization of locomotives is the process of totally rebuilding or refurbishing the locomotives when they reach end of useful service life. Modernization includes, but is not limited to, installing upgraded engine components and power electronics. Modernization is possible because the original locomotive frame can be repaired and re-used for multiple lifecycles. Modernization benefits include reduced overall equipment cost, sufficient reliability for operations, and the ability upgrade the original platform to new technology. Modernization is preferred by most Class I railway operators over buying a net new locomotive due to cost efficiencies while also capable in achieving reliable operational performance. Modernizing versus building new is also more sustainable as 60% of the platform components are refurbished and re-used. Both major North American OEMs provide modernization services.

Some Class I railroads have also maintained internal heavy rebuild shops to perform modernization services in house. One example is CSX transportation. Through a partnership with CSX transportation, CPKC developed hydrogen fuel cell battery locomotives are modernized in CSX’s Huntington Shops in West Virginia, USA shown in Figure 9. Hydrogen fuel cell battery locomotive conversion kits are designed and built in Innisfail, AB, Canada by Bilton Welding and Manufacturing. These kits are then shipped to Huntington and integrated into a fully refurbished locomotive platform. This partnership has been established as a result of this project and has significantly increased locomotive build quality. By leveraging and focusing the locomotive modernization expertise and production capability onto CSX and likewise leveraging and focusing the gas handling, pressure vessel, cooling system, and fuel cell expertise and production capability onto Bilton, future locomotives will have the required quality to deliver reliable in-service performance. The CP 1003 and CP 1004 for this project have been modernized by Bilton Welding and Manufacturing in Innisfail, AB. Future locomotive builds will follow the established partnership process.

---

[5] Refueling frequencies for hydrogen locomotives are higher as compared to locomotives fueled by diesel.

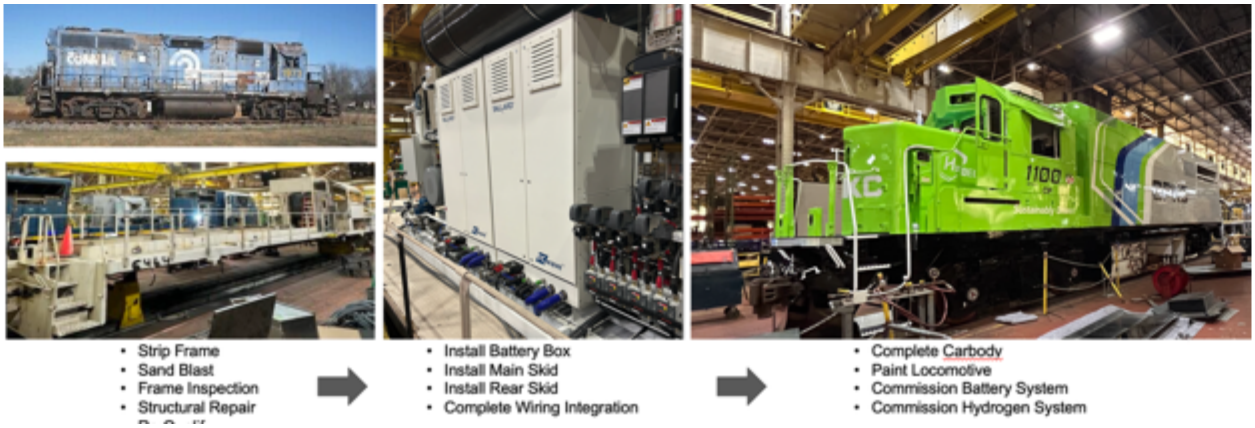

Figure 9 – CSX Huntington, WV, USA locomotive modernization facility.

3.0 – Fuel Cell Battery Hybrid Locomotive Development

Project funding from CPKC's contribution to this project has enabled the development of two (2) additional fuel cell battery hybrid locomotive conversions with the goal of demonstrating full operational integration and the ability to refine conversion kits which could scale in production. Within North America, typically Class I operators utilize a fleet of 4-axle DC traction switch or 6-axle DC traction line-haul locomotives for terminal switching and local operation between terminals and customer facilities.

Since 2020, CPKC has developed prototype versions of the 4 and 6-axle DC switch and line-haul locomotives denoted CP 1001 and CP 1002 which are shown in Figure 10. Both of these prototypes have entered into service. Being prototypes, a number of improvement opportunities have been identified through testing. Some examples include updates to improve: cooling system capabilities, fuel cell hydrogen intake and pressure regulation, simplified power electronics, and increases in onboard fuel capacities. Furthermore, from the design onset, CPKC integrated all modifications into pre-assembled conversion kits. Throughout this integration CPKC has identified several opportunities to further refine the kits into two pre-assembled skids for future locomotive builds.

Figure 10 - CPKC's CP1001 and CP1002 Low Horsepower (LHP) locomotives shown in images (a) and (b).

In 2023, CPKC applied to ERA for funding to developed two (2) 6-axle DC line-haul locomotives which would include all of the improvements to demonstrate locomotive builds which could be practically scaled up and mass produced. CPKC also had plans to acquire in-service data to demonstrate a high level of in-service reliability of the locomotives which would contribute to business decisions pertaining to further hydrogen fuel cell battery locomotive conversions.

3.1 – CP 1002 Low Horsepower Locomotive Design and Build

In October 2020, to prove the advantages of hydrogen fuel cell locomotives and the potential for locomotive conversions, CPKC initiated a program to modernize a diesel-electric Line-Haul locomotive (CP 1001) to power the existing traction motors using a combination of hydrogen fuel cells and batteries. The conversion was successful and has since completed more than 3000 miles in freight service. At that time, CPKC aimed to convert the locomotive using a retrofit "kit" concept whereby all of the zero-emission components would be installed to create subassemblies. These subassemblies would be lifted onto the platform to enable a rapid conversion of the existing diesel-electric fleet. An example of an early retrofit design is provided in Figure 11. However, being the first locomotive of its kind, the project was unable to fully achieve a retrofit "kit" concept which could be seamlessly integrated into a modernization process. In June 2021, CPKC was awarded funding from ERA to support expansion of the hydrogen program.

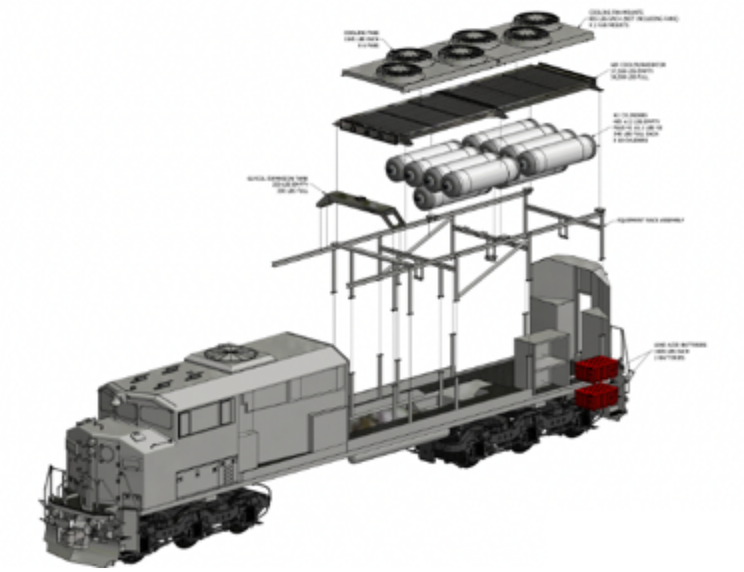

Figure 11 - Example of the CP 1001 retrofit "kit" concept showing the pre-assembled skid for the cooling fans, radiator, and hydrogen cylinders.

With an initial first round funding provided by ERA, CPKC further developed the retrofit kit concept for the 4-axle locomotive type. The resulting retrofit kit design is shown in Figure 12 which includes two preassembled “skids” which are mounted to the top deck of the locomotive and a battery box mounted under the platform. The first skid includes the hydrogen fuel storage cylinders and associated piping. The second skid includes the cooling system, fuel cells, air compressor, and power electronics mounted to a single assembly. The original car body is then lowered over the two skids back onto the top deck as shown in Figure 13 (a). The third assembly is the traction battery system which is installed as a single assembled “battery box” under the frame of the locomotive occupying the former area used for the diesel fuel tank. This is illustrated in Figure 12 and Figure 13 (b).

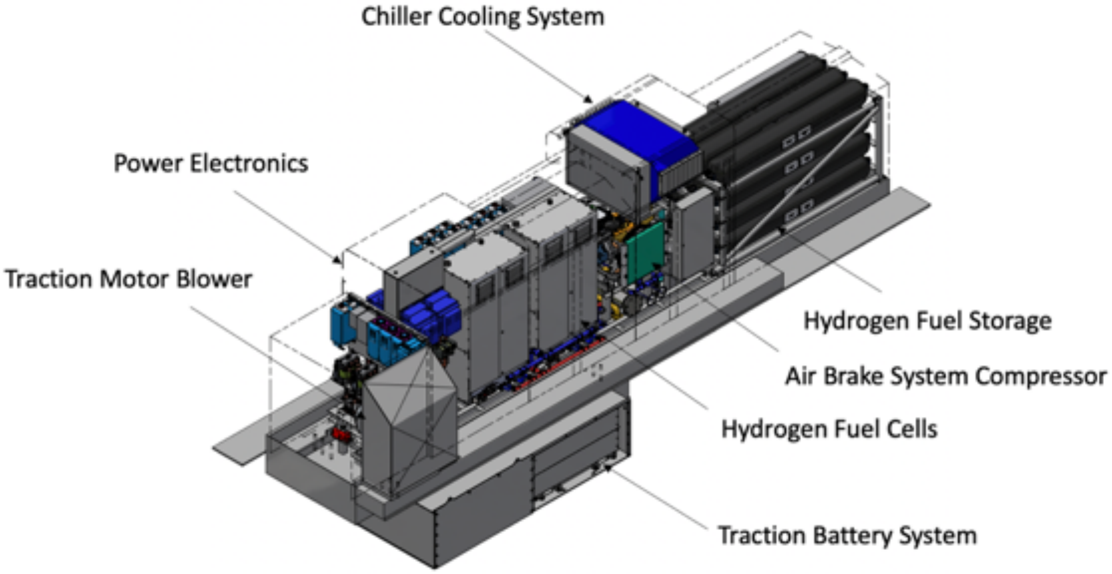

Figure 12 - Rendering of the CP hydrogen-battery electric retrofit kit. The kit consists of two pre-assembled "skids" which are mounted to the top deck of the locomotive and a traction battery system "battery box" which is mounted in place of the orginal diesel fuel tank under the locomotive frame. Note Zero-Emission Components include Fuel Cells, Batteries, and associated Power Electrics.

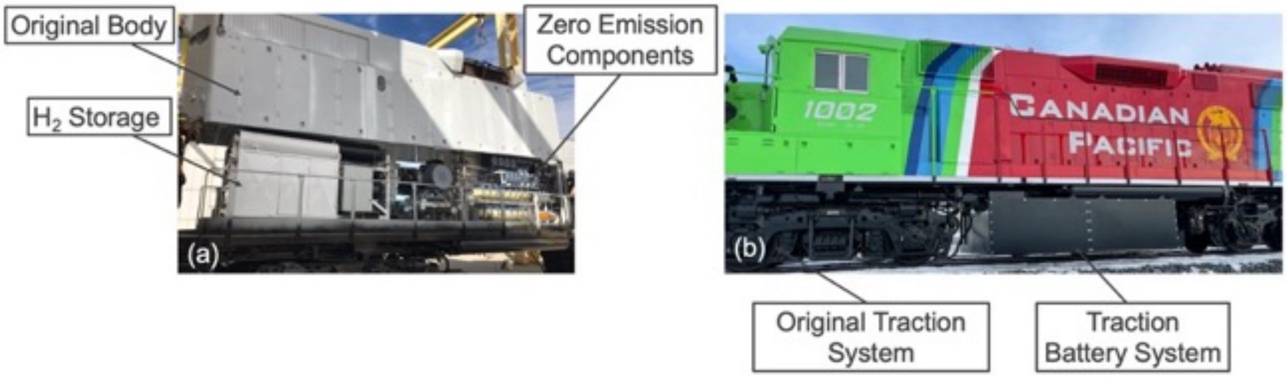

Figure 13 - (a) Pre-made zero emission component assemblies installed on the locomotive platform as "skids" with the original locomotive body being installed over top and the completed locomotive platform (b) once final assembly has been completed.

The CP 1002 locomotive is now fully commissioned has operated in twice weekly for over a year in revenue terminal switching service. The CP 1002 has been deployed and refueled several times in 2024 totaling over 800 hours of operation (not including a year of previous testing) without a single in-service failure or safety incident. The locomotive operation is identical to a diesel-electric locomotive and in additional being operated by humans, has been deployed in Remote Control Locomotive ("RCL") operation. Locomotive deployment and measured reliability have increased confidence in hydrogen fuel cell battery hybrid technology for LHP locomotive operation and motivated CPKC leadership to seek out additional Class I railway partners in North America.

With additional funding provided as part of this project, CPKC further refined the retrofit kits for the 6-axle DC locomotive type into two skids on the top deck and a battery box attached to the underframe. The main and rear skids are shown in Figure 14. The battery box remained similar to the CP 1001 however the edges have been profiled to conform the railroad clearance envelopes such the box would avoid obstructions such as the edges of concrete passenger platforms.

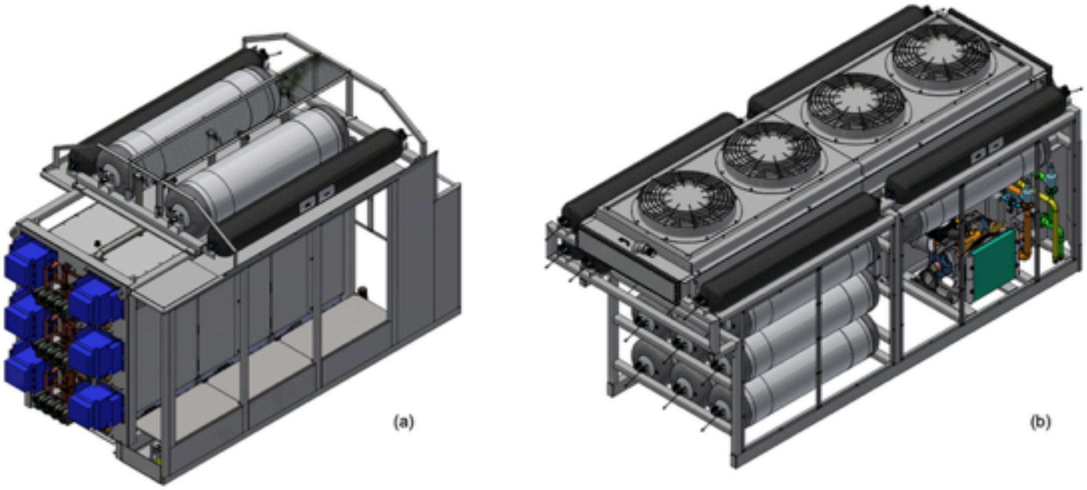

Figure 14 - Main skid (a) and Rear skid (b) for the 6-Axle DC line-haul locomotive.

The completed locomotives are number CP 1003 and CP 1004 and are shown in Figure 15.

Figure 15 – Completed CP 1003 (a) and CP 1004 (b) hydrogen fuel cell battery locomotives.

3.1.1 – Duty Cycle Analysis

An important design goal of the locomotives is to ensure that the amount of Horsepower (“**HP**”) from the zero-emission components can meet the horsepower specification of the original diesel-electric platform. Meeting the original horsepower specification can be performed with an almost infinite combination of fuel cells and batteries. Batteries have a finite amount of energy density before requiring recharging. Fuel cells can provide continuous power however they are limited by the amount of available onboard fuel. When assessing the number of fuel cells and batteries, some important factors include available space on the platform for batteries, fuel cells, and hydrogen cylinders, power demand over time or duty-cycle of the locomotive in-service, cooling capacity and environmental operating conditions. CPKC has performed several skid design iterations with Innisfail, AB based Bilton Welding and Manufacturing (“**Bilton**”) based on space constraints and duty-cycle analysis. The duty cycle analysis for the CP 1002 revealed that a typical locomotive in terminal switching operation does not utilize peak horsepower often and usually starts and stops frequently. Much time is spent in idle while various switching functions are performed (ex. throwing a switch, applying handbrakes, cutting in and testing air brakes). Therefore, more battery power is favoured in the design using the fuel cells as mainly onboard generators to recharge the batteries. The CP 1002 contains 0.86 MWh of batteries and 0.4 MW of fuel cells for a total available power of 1.26 MW (1,690 HP). The original platform is rated at 2,000 HP. In rare situations where this power demand is required, the batteries can discharge at 1.25 of their C-rating. This enables the total power output of the locomotive to reach 2,000 mechanical HP.

An example of a duty-cycle analysis is presented in Figure 16. To perform the analysis, event recorder downloads are captured from several LHP diesel-electric locomotives within CPKC’s existing operation. The power demands from these event recorders based on throttle notch and recorded engine horsepower are extracted. Using several iterations of fuel cell to battery ratios, the total power is broken down to determine fuel cell power demand and battery State of Charge (“SOC”) across several runs. Battery SOC is limited to between 20% and 80% to prevent damage to the batteries due to overcharging and over-discharging and ensure maximum battery life is maintained. The objective of the plots in Figure 16 is to determine a combination of fuel cells and batteries to prevent battery SOC limits to reach less than 20%. This will create a scenario whereby the locomotive will need to de-rate. If on a grade, the locomotive would not by itself be capable of hauling freight to the peak of the grade. This would require adding an additional unit and an operational change. The exercise showed that the CP 1002 could meet the expected duty cycle using sixteen (16) traction battery packs (or four (4) battery PODs) and two (2) fuel cells. The duty-cycle analysis does not account for regenerative braking as data were limited on the effectiveness of regenerative braking. Furthermore, terminal operations do not frequently use dynamic braking and rely on mainly on conventional air brake use. In-service testing has further validated the above design assumptions based on event recorder reviews of the CP 1002 and feedback from the train crews.

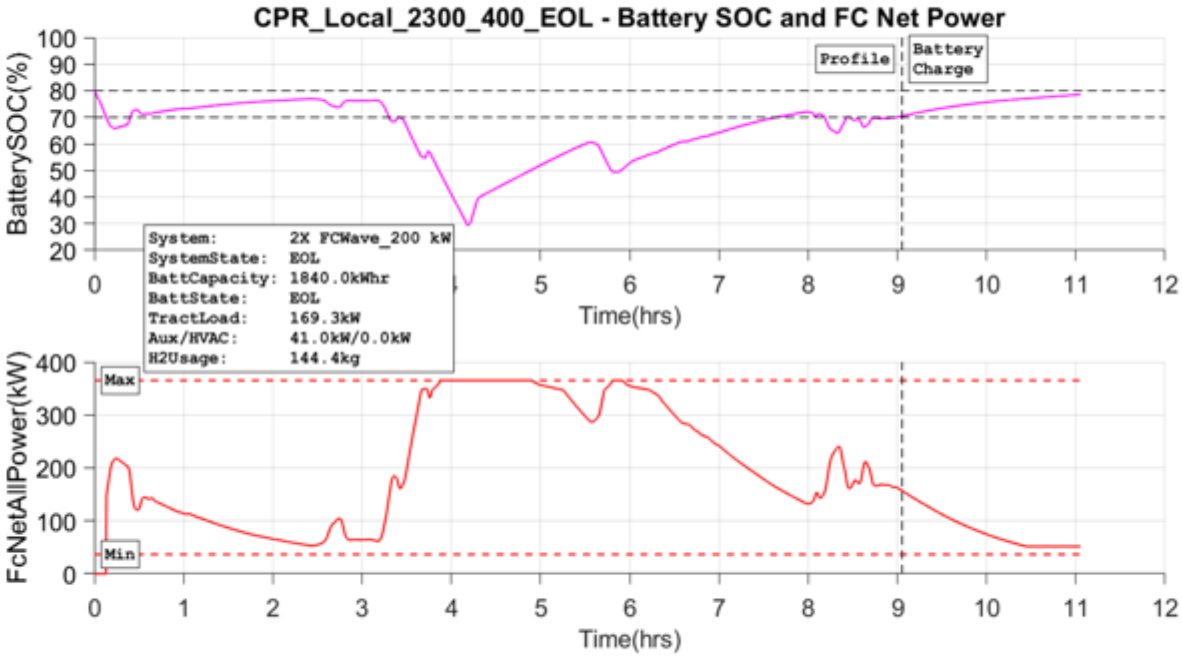

Figure 16 - Low horsepower duty cycle analysis to determine fuel cell power demand requirements and ensure a sufficient battery State of Charge (SOC) can be maintained.

The duty-cycle analysis is further expanded in this project to study operation of DC line-haul locomotives between terminals like Lethbridge “Kipp” yard and local customer facilities. Data generated during CP 1001 in-service testing proved particularly useful in validating analysis based on diesel-electric energy consumption models. Refinement of onboard power electrics and optimization of other onboard equipment also enabled increased onboard capacity of compressed hydrogen. Onboard capacity of the CP 1001 is approximately 170 kg of hydrogen. In comparison, the CP 1003 and CP 1004 locomotives contain up to 344 kg or a 102.4% increase of onboard hydrogen capacity. The results of the duty cycle analysis suggest that the locomotives would have sufficient onboard fuel to meet the current mission that existing diesel units perform on a daily basis. Local switching operations in Lethbridge depart from mechanical shops daily and work on the mainline between eight (8) to twelve (12) hours. Every evening, the locomotives are set out at the diesel fueling pad for top up and servicing. The locomotives are prepared for the following day and released. The mission is performed six (6) days per week. As such, CPKC installed the hydrogen refueling infrastructure along the same yard track as the diesel fueling pad (or island) ensuring sufficient distance for safety purposes. Overall, the CP 1003 and CP 1004 have been designed to fully replicate the current diesel-electric daily mission and duty-cycle analysis suggests sufficient on-board hydrogen fuel capacity which CPKC has validated during in-service testing.

3.1.2 – Regenerative Braking

A key feature which has been developed on both the CP 1003 and the CP 1004 locomotives is regenerative braking. This feature was not developed for the CP 1001 due to the challenges in designing, building, and validating the traction system. On the CP 1001, like a diesel-electric locomotive, power from conventional dynamic braking is dissipated through resistor grids and radiated as heat. On the CP 1003 and CP 1004, the power during dynamic braking is conditioned and passed back into the batteries.

The CP 1003 and CP 1004 have implemented regenerative braking using all 6 traction motors on each locomotive. Conventional dynamic braking resistor grids are included on both locomotives if the state of charge of the battery system is replenished. The purpose of this design is to ensure that some level of dynamic braking exists for the operator in the event the batteries reach a full state of charge. Although this is unlikely based on testing experience, it provides a level of safety and comfort for the operators that conventional dynamic braking will always be present at some level.

4.0 – Locomotive In-Service Testing

Testing of the LHP CP 1003 and CP 1004 locomotives started in CPKC's Ogden Park terminal in June 2025. The initial tests are intended to validate the systems and subsystems post fabrication and to initiate light engine tests within the terminal. CPKC progressively expanded testing to include coupling onto freight cars and performing switching operations. The reliability of the components is assessed through post-testing checks. Once initial testing and validation is completed, the CP 1003 and CP 1004 were deployed into service in CPKC's Lethbridge "Kipp" terminal. The official in-service deployment occurred on July 3rd, 2025. A summary of each test of the locomotives is provided in Table 3. Hydrogen consumption and fuel source are also tracked prior to and following each test such that emissions reductions can be calculated. Hydrogen consumption data are also gathered and stored electronically by on-board event recorders.

Prior to and following each test outlined in Figure 17:

- Pre and post locomotive and tender checks are performed
- Pre and post inspection checklists must be filled out by the hydrogen locomotive field technicians.

Figure 17 - Pre and Post-Test process for each test for the CP 1200 locomotive and tender.

Table 3 - Low horsepower CP1003 and CP 1004 locomotive testing summary.

Test #	Testing Date	Unit(s)	Route	Miles	Light Engine/ Revenue	H_2 @ Start (Bar)	T @ Start (°C)	H_2 @ End (Bar)	T @ End (°C)	H_2 Used (kg)	H_2 Source
1	June 18, 2025	CP 1003 CP 1004	Ogden Park	21.9	Revenue Switching	147.1	21.0	106.8	24.5	79.2	Green (Calgary)
2	June 23, 2025	CP 1003 CP 1004	Alyth AB to Carseland, AB	60.2	Revenue Mainline	138.5	12	48.4	19.2	177	Green (Calgary)
3	July 3, 2025	CP 1004	Lethbridge, AB to Stirling, AB	65.5	Revenue Mainline	316.3	29.4	132.5	28.1	180.6	Gray (Lethbridge)
4	July 8th, 2025	CP 1003 CP 1004	Lethbridge, AB to Aldersyde, AB	167.4	Revenue Mainline	287.3	20.2	134.2	30.2	300.8	Gray (Lethbridge)
5	July 22nd , 2025	CP 1003 CP 1004	Alyth to Ogden Park, AB	5.13	Switching	292.1	20.4	267.5	19.7	48.4	Gray (Lethbridge)
6	July 23rd. 2025	CP 1003 CP 1004	Ogden Park, AB	8.7	Switching	237.0	24.4	237.0	24.4	0	Gray (Lethbridge)
7	July 25th, 2025	CP 1003 CP 1004	Ogden Park, AB to Alyth	5.13	Switching	246.3	19.2	233.8	17.8	24.6	Green (Calgary)
8	July 31st, 2025	CP 1003	Lethbridge, AB to Aldersyde, AB	178.9	Revenue Mainline	190.0	15.8	88.5	27.0	99.7	Green (Calgary)
9	August 5th, 2025	CP 1003 CP 1004	Lethbridge, AB to Aldersyde, AB	178.9	Revenue Mainline	312.3	18.1	164.9	24.3	289.6	Gray (Lethbridge)
10	August 6th, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	81.6	Revenue Mainline	158.2	16.7	89.8	26.2	134.4	Gray (Lethbridge)
11	August 12th, 2025	CP 1003 CP 1004	Lethbridge, AB to Aldersyde, AB	180.1	Revenue Mainline	308.5	18.5	145.6	27.4	320.2	Gray (Lethbridge)
12	August 13th, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	60.6	Revenue Mainline	136.3	18.1	40.6	29.4	188	Gray (Lethbridge)

Test #	Testing Date	Unit(s)	Route	Miles	Light Engine/ Revenue	H_2 @ Start (Bar)	T @ Start (°C)	H_2 @ End (Bar)	T @ End (°C)	H_2 Used (kg)	H_2 Source
13	August 18th, 2025	CP 1003 CP 1004	Lethbridge, AB	1.1	Switching	311.2	17.1	311.2	17.1	0	Battery Only Mode
14	August 19th, 2025	CP 1003 CP 1004	Lethbridge, AB to Aldersyde, AB	176.5	Revenue Mainline	311.2	17.1	156.1	30.0	304.8	Gray (Lethbridge)
15	August 20th, 2025	CP 1004	Lethbridge, AB to Maybutt, AB	70.2	Revenue Mainline	150.9	17.9	26.4	32.5	122.3	Gray (Lethbridge)
16	September 3rd, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	71.3	Revenue Mainline	317.4	14.7	277.8	18.2	77.8	Gray (Lethbridge)
17	September 9th, 2025	CP 1003	Lethbridge, AB to Aldersyde, AB	179.2	Revenue Mainline	309.9	14.2	158.0	23.3	149.3	Gray (Lethbridge)
18	October 23rd, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	71.3	Revenue Mainline	295.2	11.8	202.1	13.8	183	Gray (Lethbridge)
19	November 4th, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	71.3	Revenue Mainline	328.3	16.4	181.4	9.3	288.6	Gray (Lethbridge)
20	November 6th, 2025	CP 1003 CP 1004	Lethbridge, AB to Maybutt, AB	71.3	Revenue Mainline	333.7	19.4	203.3	12.5	256.2	Gray (Lethbridge)

5.0 – Locomotive Results, Improvements, and Next Steps

Data gathered from in-service deployment of the CP 1003 and CP 1004 have confirmed that there is sufficient on-board hydrogen fuel to complete the mission. All systems and subsystems have been tuned, and the locomotives are demonstrating reliable operation without the requirement of utilizing diesel locomotives for redundancy. As testing hours increase, CPKC will be able to calculate industry metrics which are used to assess locomotive reliability. These metrics include Failures per Locomotive Year (“**FL/Y**”) and Mean-Time Between Failure (“**MTBF**”).

5.1 – CP 1003 and CP 1004 FL/Y and MTBF

Locomotive failures are characterized into failures which require maintenance and failures which impact the operation. Locomotives years are characterized based on the total number of locomotives and the number of years the locomotives have been in operation. For example, if you have 2 locomotives in operation for 1 year, that is 2 locomotive-years. To calculate FL/Y, divide the total number of failures by the total number of locomotive years. Current revenue service testing has results in 0 operational impacts however 1 maintenance failure has been noted. The locomotives have been in service for 4 months. Therefore, currently at a FL/Y of 3. A typical diesel locomotive has a FL/Y between 1 and 9.

Another key indicator of locomotive reliability is MTBF. MTBF is calculated by dividing the total cumulative operating time of a locomotive by the number of failures during that period. Only the CP 1004 has experienced a component failure in revenue service (which did not result in an operation impact as the locomotive could still continue to operate). The CP 1004 has approximately 240 hours of operation in revenue service over a 4-month period and 1 failure. The MTBF of the CP 1004 is therefore currently: 240 hours. This is comparable to ranges for diesel-electric locomotives. As more data are acquired, these numbers will continue to be tracked.

5.2 – Locomotive quality improvements

Overall locomotive quality of the modernization process has been a challenge. Underframe, air system, cab, and other refurbishments have required rework which ultimately delayed the commissioning process. Although these challenges have been overcome, the functions of modernization the locomotive cores have been transitioned to CSX’s Huntington, WV locomotive modernization facility as part of a partnership between CPKC and CSX. Doing so has reduced commissioning time from 6 months to 2 weeks. This learning and project change has been critical in opening the commercialization potential for these locomotives. With a total focus on kit production, Bilton has increased quality and now has resources to focus on kit production scale-up. This is enabling overall platform cost reductions which have brought the locomotives within reach of Tier IV diesel-electric modernizations.

Additional learnings have also included further refinements to the conversion kits. By relocating beams within the locomotive frame which are installed to provide ballast weight, a single unified top pre-assembled skid can be build. This further reduces cost by removing connection points and various other build steps. This is being demonstrated on CPKC's 2025 6-axle builds.

5.3 – Next Steps

More production locomotives of both the 4-axle and 6-axle versions developed through ERA projects will be built. The locomotive conversion kits are all produced in Alberta and the modernization of the locomotives is performed in West Virginia. The goal of developing 20 total locomotives is to deploy all of these units for a one-year period. Doing this will enable gathering of 20 locomotives years' of reliability data. Statistics will be used to validate FL/Y and MTBF rates which will then be used to justify further scale up. During this process locomotive design improvements both on hardware and software are expected.

6.0 – Hydrogen Refueling Infrastructure

To meet the future needs of freight rail operations, a low-carbon hydrogen supply chain is required to emulate the complex diesel fuel supply chain that is currently in place to support diesel locomotive operations. To control costs and optimize operations to reduce delays, North American railroads have invested heavily to improve locomotive fuel efficiency and fueling infrastructure. To meet the needs of freight rail operations a complex fuel delivery supply chain and system consisting of fueling both at fixed point fueling locations or DTL via mobile fueling trucks is required. Fixed point fueling often occurs at CPKC's mechanical shop facilities at larger terminal locations.

As such, in this project, CPKC and Air Products collaboratively installed fixed-point refueling infrastructure and a mobile refueler. The fixed-point refueling has been built to utilize low carbon "blue" hydrogen supplied from Air Products' Net-Zero Hydrogen Energy Complex in Edmonton, AB. This required the infrastructure to consist of on-site liquid hydrogen storage tanks and equipment to evaporate, compress, and dispense gaseous hydrogen into the locomotives. The mobile refueler also contains portable versions of this equipment to achieve the same function.

This refueling station is equipped with two dispensers to support a typical DTL (Direct to Locomotive) fueling approach that is followed at other CPKC mechanical shop facilities at larger terminal locations. Blue hydrogen supplied by Air Products' Net-Zero Hydrogen Energy Complex in Edmonton, AB is supplied via transport truck to site and stored in a 25,000 US GAL vessel. The liquid blue hydrogen is vaporized and then compressed and stored in gaseous form. The hydrogen gas is then dispensed into the locomotives to fuel them.

The high-level site layout plan developed to accommodate this process includes the following major equipment:

- 1 x 25,000 US GAL cryogenic liquid H2 storage vessel
- 6 x high pressure gaseous storage vessels at 7,000 psig
- 2 x cryogenic liquid H2 compressor systems
- 2 x automated H35 dispensers to fill at 250 kg/hour
- 1 x hydrogen cascade and controls manifold
- 5 x ambient air vaporizers

Utility equipment that remained CPKC scope included:

- 1 x 480VAC, 3-phase transformer
- 1 x instrument air skid

Construction on site began following a site evaluation in July 2024. Criteria considered when selecting the pad location included: track height, available space to accommodate a 25' radius for the Class I Div II Group B zone classification of the cryogenic storage vessel, available space to accommodate a 75' radius to be kept clear of ordinary combustible materials and air intakes, proximity to other existing flammable materials stored on site, proximity to inhabited buildings, and ensuring sufficient distance from overhead wires. Distances from overhead wires and existing fuelling infrastructure are defined in documentation provided by Air Products based on known standards and best practices. Barriers and grading activities are also included in support of the DTL truck deployment. Photos of the overall construction process are shown in Figures 18 – 23.

Figure 18 - Air Products site evaluation at CPKC's Kipp Yard terminal.

Figure 19 - Fixed-point refueling infrastructure site plan.

Construction work for the fixed-point refueling station began in the fall of 2024 starting with grading, piling, and concrete foundation pouring (see Figures 20 and 21) . Trenches were dug, light posts were installed, and some electrical wiring was pulled as well to start (see Figures 22 and 23).

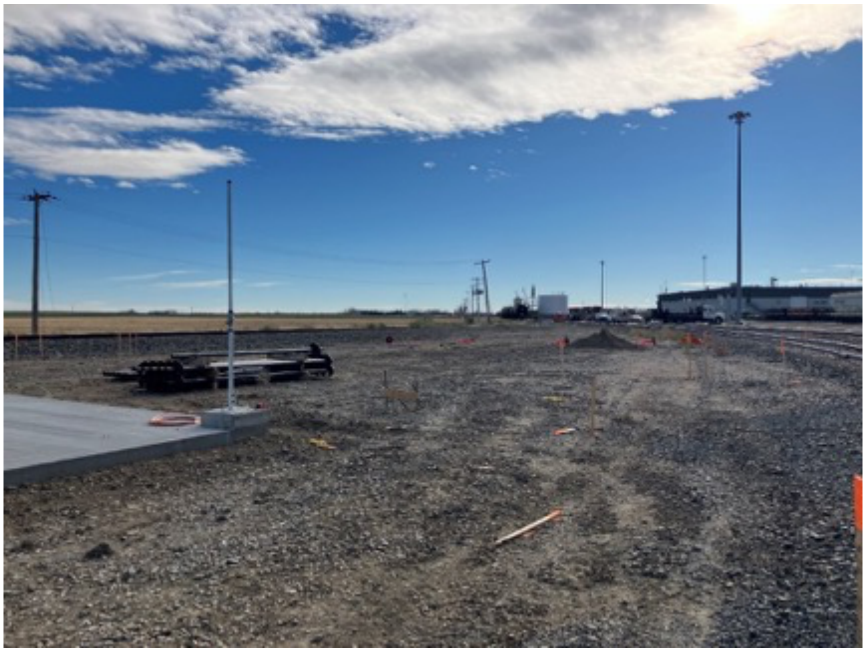

Figure 20 - Initial construction at site – grading, concrete foundation pouring.

Figure 21 - Initial construction at site – concrete pouring, electrical work, lighting post installation.

Figure 22 - Trenching for hydrogen supply line vault.

Figure 23 - Construction at Kipp Yard terminal as in August 2025

DTL refueling of the CP 1004 locomotive in CPKC's Lethbridge "Kipp" terminal is shown in Figure 24. In the Figure, the DTL truck fuel dispenser and grounding cable are attached to the locomotive Figure 24 (a). A photo taken further away shows the locomotive and DTL trailer in Figure 24 (b). The concept of this mobile refueler is also similar to the DTL approach followed at other CPKC mechanical shops and just like the concept behind the fixed-point refueling infrastructure, liquid hydrogen is trucked in, compressed and vaporized onboard the mobile refueler, and directly dispensed into the locomotives.

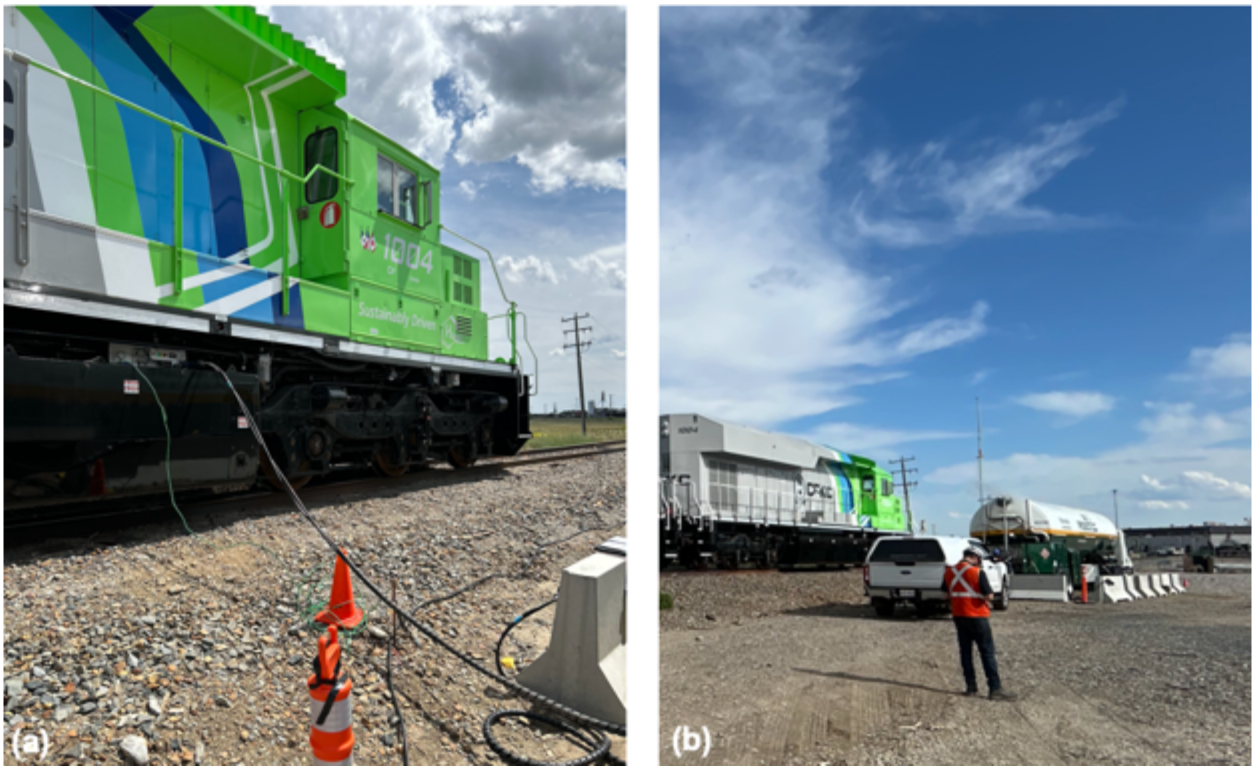

Figure 24 - (a) CP 1004 showing dispenser nozzle and grounding cable attached to the locomotive and photo (b) showing DTL Refueler attached to the CP 1004 at CPKC's Lethbridge "Kipp" terminal.

To accommodate the temporary fueling solution at site, the gravel on the ground was leveled, the 75' radius was cleared of ordinary combustible materials, 3-phase explosion proof electrical outlets, a heater, and two grounding rods were installed.

Lighting posts and barriers were also installed as a safety means for light and to protect the trailer and employees from vehicular traffic, with the intention to reuse these posts and barriers for the fixed-point infrastructure.

Some other considerations that needed to be assessed prior to installing this refueler included:

- accommodation of 15' from center of the rail to the edge of the trailer to comply with CPKC policy,
- available space to accommodate a 25' radius for the Class I Div II Group B zone classification,
- available space to accommodate a 75' radius to be kept clear of ordinary combustible materials and air intakes,
- proximity to other existing flammable materials stored on site,
- proximity to inhabited buildings,

- ability to comply with a min. 50’ horiztontal distance from the vertical plane of overhead electrical wires; and
- ability to comply with a min. 15’ horizontal distance between the vent stacks on the trailer and personnel cab of the locomotives.

A photo of the L to G refueler and the fixed-point refueling infrastructure are shown in Figure 25 and Figure 26 below.

Figure 25 - L to G Refueler on-site in Lethbridge, AB.

Figure 26 - Fixed-Point refueling infrastructure.

7.0 – Mechanical Integration and Maintenance Procedures

This section describes the steps taken by CPKC in the development of maintenance procedures and overall integration of hydrogen fuel cell battery locomotive maintenance into existing CPKC mechanical facilities (i.e. shops). As part of this project, CPKC developed a maintenance and operational manual for the locomotives. This manual includes regular maintenance requirements by modifying and enhancing existing diesel-electric locomotive Quality Locomotive Maintenance Inspection ("**QLMI**") instructions. The manual also includes instructions for maintaining/repairing the propulsion and traction system components. On-site training of mechanical staff has been performed. CPKC also hired a Specialist Hydrogen Locomotive Field Testing as on-site mechanical shop support in Lethbridge. The locomotive cabs are equipped with starting procedures and train crews have also been trained with operation details.

8.0 – Commercial Readiness Planning

This section provides background information on heavy-haul freight railroading which includes an assessment of the overall commercialization opportunity. The opportunity to commercialize hydrogen-fuel cell battery electric locomotives requires organizations to have a decarbonization vision and mindset. The opportunity to commercialize also requires continued support from the investment community and government. Currently freight railroad performance is measured on freight train reliability and on-time performance which requires reliable locomotives capable of hauling significant tonnages over long distances. Therefore, as the sector increasingly deploys alternative powered locomotives, including hydrogen-fuel cell battery electric locomotives, each unit must perform similar to the current diesel-electric fleet.

8.1 – Locomotives in Heavy-Haul Operation

Six (6) Class I railway companies, including CPKC operate throughout North America across the regions shown in Figure 27, as well as several dozen regional and short line companies. Comprising the backbone of intercity surface freight transport in Canada and the U.S., the network of railways is served by an estimated 40,000 diesel-electric locomotives. Most of these units will remain in service until 2050 and beyond, kept in good working order through industry-standard programs of scheduled modernization and retrofit.

Approximately 42% of these locomotives or 16,150[6] are used for terminal switching and local mainline use by moving freight between terminals and 3rd party loading and unloading facilities. These locomotives are considered low horsepower locomotives with up to 3,000 HP (typically between 2,000 HP to 3,000 HP). Low horsepower locomotives burn an annual average of 171,000 L (45,174 US Gals) of diesel fuel per locomotive. As an industry, in North America alone, 2,761,650,000 L (718,029,000 US Gals) of diesel fuel is burned by low horsepower locomotives each year. This generates an estimated 10,513,650 tCO_2e every year.

---

[6] Source: RailINC Corporation – 2021 North American Locomotive Report, https://public.railinc.com/about-railinc/research-reports

Figure 27 - Map of the North American Class I railway networks.

As emissions reduction commitments from both industry and government begin to reach critical milestones, a greater need to find alternatives will occur. The current industry OEMs propose battery only solutions which cannot be integrated into locomotive modernizations in the form of retrofit kits due to additional weight and insufficient range potential to meet operational requirements. Furthermore, current OEMs have made no public commitments to explore hydrogen fuel cell technology. Battery electric locomotives can only generate maximum horsepower for up to forty (40) mins per the manufacturer's specifications. These locomotives are simply incapable of meeting the demands of Canadian and North American railroads who must navigate steep ascending grades in cold climates. Recharging times do not enable replication of current diesel refueling times and recharging infrastructure is complex and may require significant utility upgrades as more locomotives are incorporated into terminals. Finally, battery locomotives require duplication of assets which does not align with current industry practices namely Precision Scheduled Railroading (PSR).

Additional pressures in the United States for freight railways to transition to zero-emission locomotives technologies are being driven by the California Air Resources Board (CARB). CARB has proposed a legislated requirement that starting in 2030, all new switch and industrial locomotives must be zero emission in order to operate within the state. Although this regulation has been withdrawn, eventually impacts are likely to occur to the two (2) largest Class I railroads in North America: Union Pacific ("**UP**") and the BNSF. As such, it is expected that this could ultimately drive that all modernized LHP diesel-electric locomotives will have diesel engines removed and replaced with either fuel cells, batteries, or both. More recently the OEMs[7] have acknowledged hydrogen will be required as part of the North America solution suite to decarbonize. To achieve significant reductions in

---

[7] Source: Train's Magazine Article: "Wabtec: Hydrogen is the fuel of the future", https://www.trains.com/trn/news-reviews/news-wire/wabtec-hydrogen-is-the-locomotive-fuel-of-the-future/

railway sector GHG emissions within this timeframe, any solutions must be practically applicable to existing locomotives. This represents a market opportunity for hydrogen fuel cell battery electric locomotives as products of a conversion service.

CARB has temporarily withdrawn the requirement for zero-emission HHP locomotives to be purchased after 2050 instead potentially creating a Tier V emissions standard. The consequence to this is that Tier V refers to criteria-air-contaminants (CACs) and not necessarily GHG emissions such as CO_2, CH_4 or N_2O. To achieve Tier V post exhaust treatment systems will be added to diesel engines which would not have an impact on rail sector climate change objectives. Hydrogen fuel cell battery electric locomotives solve both CAC and GHG issues and therefore it is believed that continued development even in HHP applications is necessary and markets will evolve in this space albeit after LHP locomotives are established.

This report has already discussed the disadvantages of battery only locomotives. Long recharging times, infrastructure availability, and asset duplication are just some of the drawbacks. However, there are still large Class I railways who will continue to rely on the OEMs to provide the solution to climate change. Railways are justifying battery only locomotives for LHP operation as it is believed there are many opportunities for downtime within the operation. Based on CPKC's experience this is simply not the case. Adopters of battery only locomotives will reach a point where operating costs will be too high to compete with Class I railroads who have invested in hydrogen fuel cell technology. Most customer facilities with switch operations may opt to use battery only locomotives as locomotives at these facilities are used sparingly. Finally, a general concern for hydrogen gas and associated fires/explosions has left some operators in favour of battery only solutions despite the fact that batteries also have fire/explosive potential if not properly integrated and maintained. Following CSA, NFPA, ABSA, and other governing body standards and best practices helps to reduce risks and these associated concerns. Hydrogen portability, low-carbon generation potential, and ability to eliminate almost all downstream GHGs and CACs make this fuel source desireable for railway applications.

9.0 – Technology Success Metrics

The project success metrics are shown in Table 4. This project has reasonably achieved all of the success metrics laid out at the onset of the project.

Table 4 - Project defined success metrics and achievements.

Success Metric	Commercialization Target	Project Target	Actuals	Comments
Cost – 6 Axle DC (per Unit)	<$2.5M	<$5M	6 Axle DC - $8.825M per unit	Increased costs necessary to ensure enough onboard hydrogen could be installed

				to meet the mission. Considerable redesign over the CP 1001 to improce overall quality, robustness, and reliability contributed to higher costs.
Cost – H2 Infrastructure	<$15.5M	<$15.5M	Fixed-Point - $7.2M Mobile Refueler - $1M	Internalizing infrastructure construction through CPKC's facilities team significantly reduced contractor costs. Signed long-term hydrogen supply agreement with Air Productions preventing need to outright purchase the on-site tanks, compressors, dispensers.
Locomotive Fleet Interoperability	Same as project target	Unit operates in any train as lead and trail	Demonstration in lead and trail. Solo switching and mainline operation without diesel locomotives	
Energy Efficiency	40%	35%	Data acquired from over 12 mainline tests, efficiency modeling of data shows 38% efficiency	
Fuel Availability	Delivery and Dispensing of 2500 kg/week	Delivery and dispensing of 1500 kg/week	3500 kg/week delivery capability	
Re-fueling Times	45 mins	<1 hr	2 – 3 hours with fixed-point and mobile refueling due to significant increases in onboard hydrogen capacity versus initial design capacipty assumptions	Increased onboard hydrogen requires more dispensing time. Addition of more compressors and chillers in the future will enble CPKC to achieve the commercialization target. Current refueling operation does not impact the operation.
GHG Emissions Intensity	3.49 tonnes CO_2e/tonne H_2 Assumes 95% CO_2e capture efficiency less a 20% penalty for energy and transportation	3.955 tonnes CO_2e/tonne H_2 Assumes 85% CO_2e capture efficiency less a 20% penalty for energy and transportation	14.064 tonnes CO_2e/tonne H_2 Average based on mix of green and grey H2 used during project period.	Actuals based on a mix of green, grey hydrogen. Blue hydrogen will be available by Air Products in 2026.

Time between Fueling Events	1 time per week	< 4 times per week	3.5 times per week	Locomotives are setup to utilize a tender. This will be needed to achieve the commercialization target
Range (miles)	240	120	203.9	Further software optimization will enable CPKC to reach the commercialization target.

10.0 – Lessons learned and Challenges

This project has successfully deployed two hydrogen fuel cell locomotives into CPKC's revenue service. Overall the locomotives have and continue to perform well. However, any fault within the systems is quickly observed and reported by the operators. Faults are mainly due to fuel cell operation during start-up and shutdown. As such, concerted efforts to develop fault exception handling to mitigate operator intervention have been performed. This process requires all faults to be reported, an immediate data analysis and drilldown to be performed, followed by "mini sprints" or software released to remedy the challenges. The process overall has required significant leadership and team discretionary effort. Further making this challenge harder is that these locomotives are competing with almost 70 years of diesel-electric locomotive innovation in rail. In order to continue momentum for the energy transition, it is absolutely critical to ensure issues are quickly investigated but more importantly corrective actions incorporated quickly. The benefit of this process is that the robustness and quality of the locomotives has improved significantly.

Another challenge has been water handling and ingress. The fuel cells generate significant amounts of water for the exhaust. Power provided to and delivered from the fuel cells requires power electronics which can be damaged by water and moisture. Significant efforts to seal the locomotives, fuel cell exhaust (see Figure 32 (a)), and within the fuel cell enclosures have been made. Faults from water ingress within the fuel cells cannot be recovered per CPKC processes without an inspection to avoid component damage, risks of fire, or another other safety risks. Preventing these faults has been a continuous challenge working with Bilton, Ballard, and CPKC team members. Future builds include a common exhaust manifold which was previously advised against from the vendor as trace amount of hydrogen could get trapped. Bilon and CPKC have found ways to mitigate these risks. A common exhaust manifold will prevent the need for venting mesh and reduce overall water ingress sources (See Figure 32 (b)).

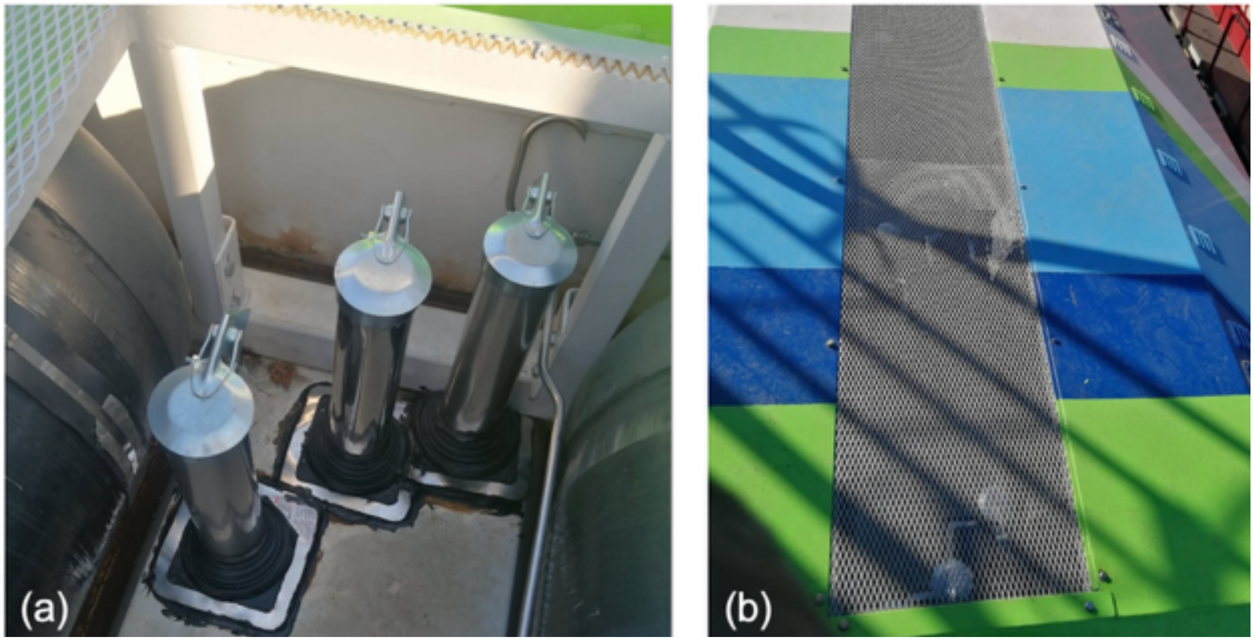

Figure 28 - (a) Sealing of fuel cell exhaust pieps for 3 fuel cells and (b) wire mesh installed for hydrogen venting over fuel cell enclosures.

Additional challenges centered around people and development. As the locomotives entered service, the team transformed from a technical and design team into an operating team. This transition was particularly difficult for some of the technical staff. It was important to ensure technical staff gained field experience to improve the hardware and software designs including modifications. However, it was equally important to hire at the appropriate time to alleviate the extended hours put on technical staff. Training documentation was extremely time consuming to create and rollout to field/shop mechanics require extensive work as well. Many of the technologies onboard the locomotive are new even though 60% of the original platform is reused. Significant learnings regarding human factors required relentless software updates to improve useability and maintainability of the platforms.

11.0 – GHG Monitoring

Please see attached report from CPKC’s Sustainability group.