The CP Hydrogen Rail Initiative

Project ID: E0161335

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1.0 - Introduction

This report has been created in support of the “CP Hydrogen Rail Initiative.” This project has been executed using funding awarded to the Canadian Pacific Kansas City (“**CPKC**”)[1] railway company by Emissions Reduction Alberta (“**ERA**”) in June 2021.

The funding received by ERA of $15M matched CPKC’s investment of an equal $15M for a total of $30M for the project. The total funding 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 from compressed hydrogen gas and atmospheric oxygen through an electrochemical 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 compressed hydrogen gas as a fuel source or feedstock. As such, CPKC used 50% of the awarded funding to purchase and install hydrogen generation and refueling infrastructure necessary create fuel for the locomotives. This included two (2) electrolysers which can produce hydrogen from electricity and water. One electrolyser is in CPKC’s Ogden, AB (Calgary) terminal and produces “green” hydrogen powered by renewable energy from an existing 5 MW solar farm on CPKC’s head office campus. The other electrolyser is in CPKC’s Clover Bar, AB (Edmonton) terminal and produces “gray” hydrogen powered by electricity sourced directly from the Alberta utility grid.

The combination of locomotives and hydrogen refueling infrastructure has enabled CPKC to demonstrate the feasibility of hydrogen fuel cells and batteries in freight railroad operations. Both locomotives have been tested and demonstrated in revenue service. Currently, both locomotives remain in service for rail operations.

This report describes the results of the CP Hydrogen Locomotive Initiative including details of the locomotives such as, but not limited to: overall design and build, in-service testing, and design refinements. The report further details installed refueling infrastructure including, but not limited to: site selection, procurement, specifications, construction, commissioning, and refueling of the locomotives.

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[1] At the time of the funding approval, CPKC was the Canadian Pacific (“**CP**”) railway company. CPKC is the result of a merger which was finalized in April 2023 between CP and the Kansas City Southern (“**KCS**”) railway company. The new entity is referred to as Canadian Pacific Kansas City or **CPKC**.

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.

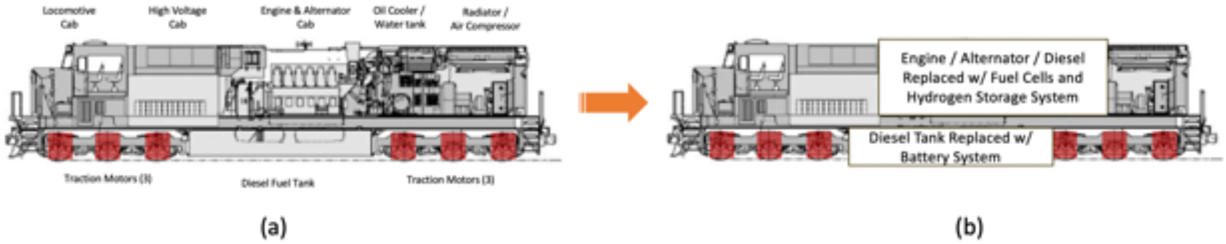

Figure 1 - Illustration showing the high-level systems of a diesel-electric locomotive (a) and the locations which are replaced during the conversion process to create a hydrogen-battery fuel cell locomotive (Source: Deviant Art).

The re-use process described above is known within the North American freight rail industry as locomotive "modernization." Currently, most 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 a battery-electric locomotive as the technology of choice for North American Class I railroads to support emission reductions. These locomotives 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 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 only available for testing in 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.

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[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.

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) (Sources: Wabtec, Progress Rail).

Both battery-electric locomotives shown in Figure 2 can be recharged. Charging locations are physical and must be installed at fixed locations. Class I railroad operators who have purchased these locomotives will require and have purchased additional locomotives to support continuous operation due to the lengthy recharging time requirements. Therefore, for every locomotive purchased, 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 a battery-electric locomotives within terminal operations, these locomotives cannot replicate the efficient operations established with diesel-electric locomotives within the current industry landscape. More specifically, 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 quantitative and qualitative comparison between battery-electric and hydrogen fuel cell battery electric locomotives are shown in Table 1. 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 - 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*
Estimated 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	High	Low
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.

2.3 – 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 is flowed 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

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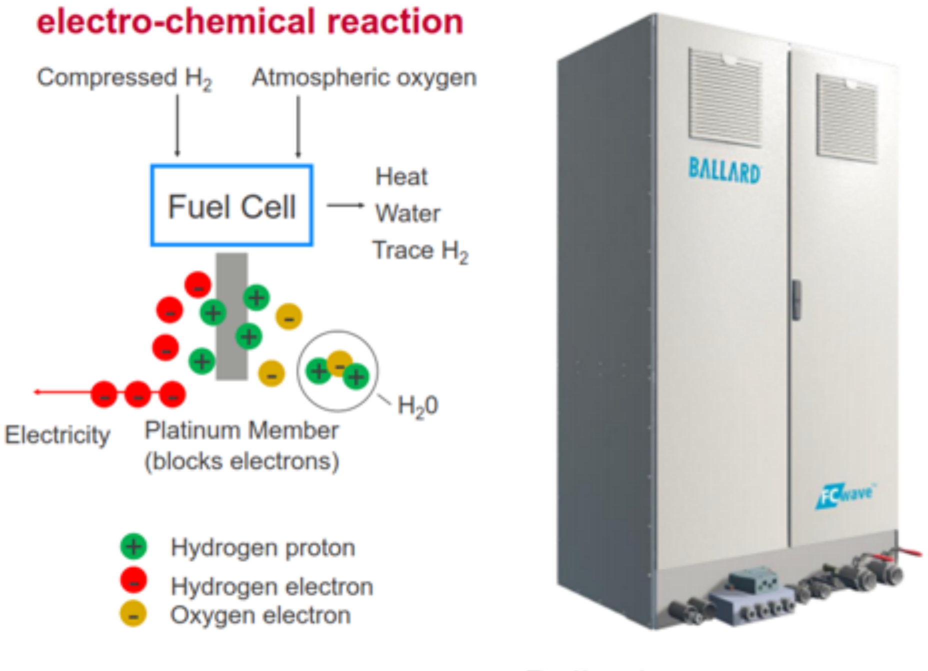
[3] A tender car can be attached to a locomotive and enables additional hydrogen to be carried as fuel to extend range.

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 3. The total power output of each fuel cell is 200 kW (268 HP).



Ballard 200kWh Fuel Cell

Figure 3 - Illustration of the electrochemical reaction within the fuel cell stack and the production PEM fuel cell used in the locomotives (Source: Ballard Power Systems).

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 4.

Figure 4 - 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 5). 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 5 - Hydrogen Hybrid switcher locomotive (Source: RailPicture.net photo Nathan Zachman)

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 (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

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

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 6.

Figure 6 - CP 1001 hydrogen fuel cell battery hybrid locomotive. North America's first for line-haul operation.

2.4 – 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, CPKC has developed a tender car (CP10001) for HHP operation discussed later in this report.

2.5 – Locomotive Modernization

Locomotives are currently refurbished and upgraded in a handful specialized facilities across North America. For example, CPKC regularly sends its 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 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. Modernizing versus building new is also more sustainable as 60% of the platform components are refurbished and re-used. Major North American OEMs provide modernization services. One example is Wabtec Corporation with a state-of-the-art facility located in Forth Worth, TX, USA.

3.0 – Fuel Cell Battery Hybrid Locomotive Development

Project funding from CPKC's contribution enabled the development of two (2) additional fuel cell battery hybrid locomotive conversions. Within North America, typically Class I operators utilize a fleet of 4-axle DC traction switch, 6-axle DC traction line-haul, and 6-axle AC traction line-haul locomotives. CPKC has already developed the 6-axle DC traction line-haul locomotive (CP 1001) however aspired to cover all other locomotive variants within the industry. Within this project, CPKC built two (2) additional prototypes to cover the 4-axle DC traction switcher and 6-axle AC traction line-haul locomotives. These locomotives have been completed and are numbered the CP 1002 and CP 1200 respectively. In addition, CPKC commissioned the build of a tender car (CP 10001) to support the increased hydrogen capacity requirements of the CP 1200 for HHP operation. All constructed locomotives including the CP 1001 are shown in Figure 7.

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

Figure 7 - CPKC's CP1001 and CP1002 Low Horsepower (LHP) locomotives shown in images (a) and (b) and the CP1200 High Horsepower (HHP) locomotive and CP10001 tender shown in (c).

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.

With additional funding and a focus on LHP locomotives, CPKC further developed the retrofit kit concept. The resulting retrofit kit 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 8 (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 8 (b).

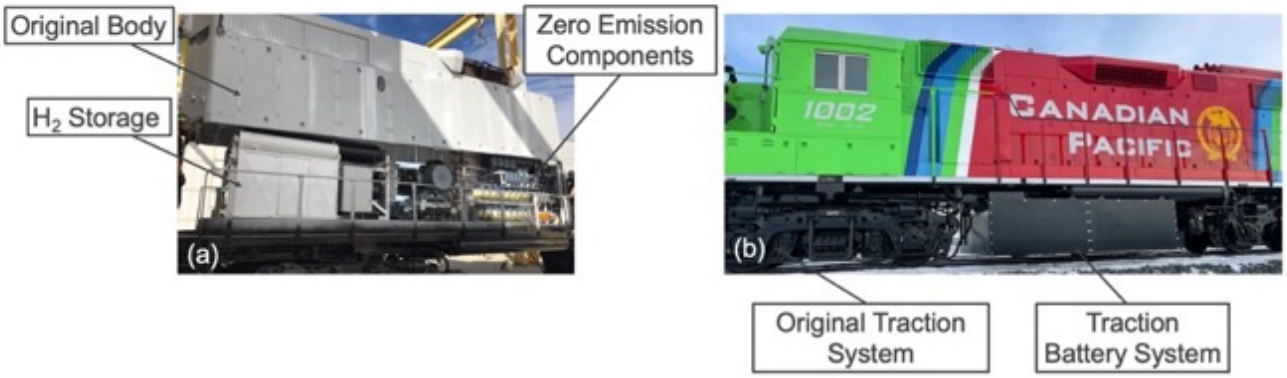

Figure 8 - (a) Pre-made zero emission component assemblies installed on the locomotive platform as "skids" with the original locomotive body being installed over top and the completed locomotive platform (b) once final assembly has been completed.

The CP 1002 locomotive is now fully commissioned and operating twice-weekly in revenue terminal switching service. The CP 1002 has been deployed and refueled over 25 times in 2024 totaling 500 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.

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 combinations 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 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 original platform is rated at 2,000 HP.

An example of a duty-cycle analysis is presented in Figure 9. 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 9 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.

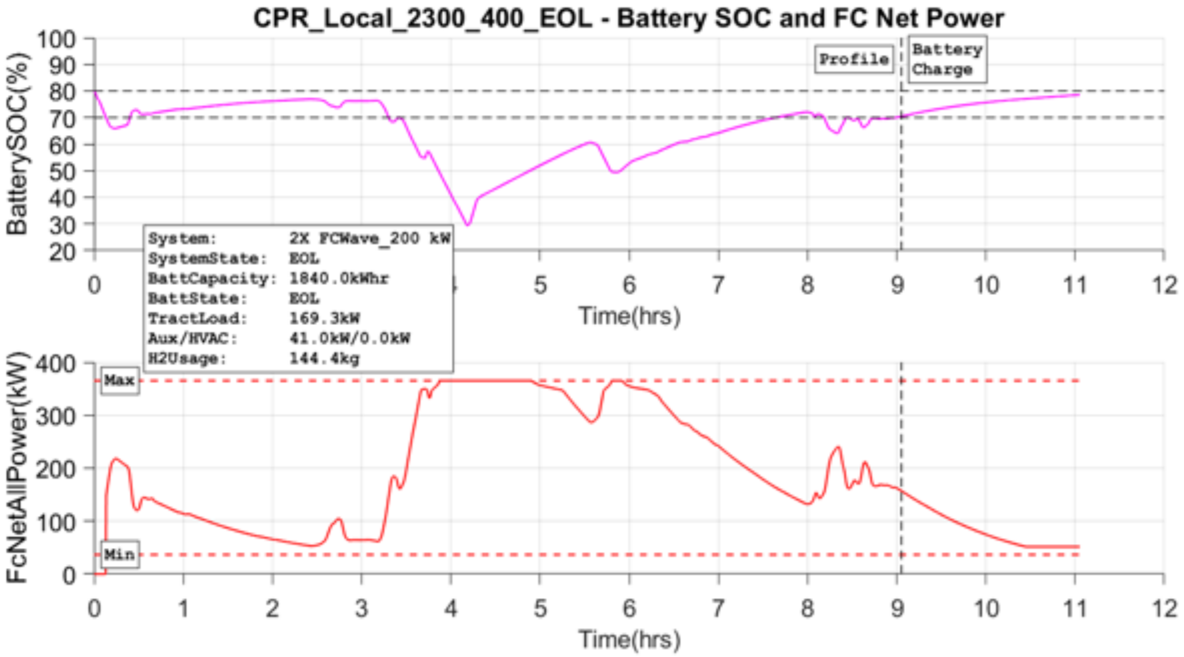

Figure 9 - Low horsepower duty cycle analysis to determine fuel cell power demand requirements and ensure a sufficient battery State of Charge (SOC) can be maintained.

3.1.2 – Regenerative Braking CP 1002

A key feature which has been developed on both the CP 1002 and the CP 1200 locomotives is regenerative braking. On the CP 1002 and CP 1200, the power during dynamic braking is conditioned and passed back into the batteries. The CP 1002 and CP 1200 have different regenerative designs. Both of these designs have been submitted and are patent pending.

3.2 – CP 1200 High Horsepower Locomotive Design and Build

The HHP CP 1200 locomotive is considerably different in comparison to the CP 1001 and CP 1002 LHP locomotives. The locomotive is required to output 40% more horsepower. The traction motors utilize Alternating Current ("**AC**") as opposed to Direct Current ("**DC**") which requires a difference traction system design. Current industry diesel-electric locomotive platforms utilize proprietary traction systems. CPKC unsuccessfully initiated the current industry OEMs to facilitate integration of CPKC's zero-emission fuel cell and battery systems into the existing AC traction system. The original systems also posed other challenges in that since the inception of AC traction, the traction inverters maintained an air-cooled design. Air cooled power electronics take up significantly more space in comparison to their liquid-cooled counterparts. Moving to liquid-cooled traction power electronics creates valuable space which could be used for additional onboard hydrogen storage. CPKC concluded that designing and building a liquid-cooled AC traction system would provide longer-term benefits to the HHP locomotive and its operation. To do this, CPKC engaged a local Calgary, AB vendor known as Integral Control Systems. This section describes design considerations of the CP 1200 HHP hydrogen fuel cell battery electric locomotive from duty-cycle analysis to design iterations.

3.2.1 – Duty Cycle Analysis

Similar to CP 1002, event recorder downloads are used to determine the power demand requirements of the HHP locomotive fleet and to determine the proportion of the required number of batteries to fuel cells to satisfy the power demand. CPKC's most challenging terrain is west of Calgary through the Canadian Rocky Mountains. HHP locomotives are used in Grain, Potash, Sulfur, and Coal services. These commodities are shipped to west coast ports for export. The exports of these commodities is extremely valuable and a significant contributor to the Canadian Gross Domestic Product ("**GDP**") and domestic economy overall. Therefore, when building a HHP locomotive, the unit must be able to haul the freight tonnages through these regions including up mountain grades in order to practically be used on the CPKC network. Therefore, event recorder downloads from locomotives in Canadian bulk train operations are analyzed to assess the power requirements and determine the required quantities of fuel cells and batteries.

In the case of the HHP locomotive simulations, CPKC discovered that the batteries failed to support enough continuous power during ascending grade movements in bulk train operation. This is due to the maximum capacity or energy density of the battery packs. Even the best battery pack could not provide sufficient power long enough for practical operation without needed CPKC to add an additional locomotive for each locomotive operating along these routes.

When the simulations are repeated with approximately 70% fuel cells and only 30% of batteries, no de-rating of the locomotive is required. The consequence however is that insufficient space remains on-board the locomotive for enough hydrogen supply. This is why CPKC proceeded to build a hydrogen tender car discussed later in this document. An extract of the duty-cycle analysis is shown in Figure 10.

Figure 10 - CP 1200 HHP locomotive duty-cycle analysis for a locomotive operating across the Canadian Rocky Mountains.

3.2.2 – Locomotive Tender

Through the design process and duty-cycle analysis it became apparent to CPKC that meaningful run-time and ranges could be achieved in LHP locomotives with the existing amount of onboard space. However, for HHP locomotives, run-time and range would not be operationally viable using onboard hydrogen fuel only. Therefore, CPKC decided to work to develop a tender car which would enable additional hydrogen fuel for the locomotive to be transported and consumed in motion. Tender cars have been used in rail operations since steam engines and are still used today in operations where Compressed Natural Gas (“**CNG**”) is injected into Internal Combustion Engines (“**ICE**”) engines in order to reduce diesel fuel consumption.

Association of American Railroads (“**AAR**”) M-1004 outlines standards and recommended practices for crashworthiness which tender cars must meet in order to qualify for interchange. The AAR *Manual of Standards and Recommended Practices* (“**MSRP**”) is written through collaboration between subject matter experts within the rail industry including Class I railway members, OEMS, short lines, research organisations (e.g. National Research Council of Canada, MxV Rail), and external consultants. The manual brings all available knowledge together to provide standards and guidelines within the industry to reduce overall risk and maintain safety within the freight rail industry.

M-1004 outlines a crashworthiness methodology which requires a series of quasi-static and dynamic load cases to be assessed on all tender designs. The standard includes the requirement to utilize advanced simulation tools common within engineering design firms, including but not limited to, the following: LS-Dyna, ABAQUS, and ANSYS. The tender uses crash panels which are designed to resist a 286,000 lbs vehicle 1’x1’x10’ steel impactor ramming the tube compartment at 25 MPH against a concrete wall. This case has been determined by industry experts to be the worst impact load case the tender car would see. Note that this case is extremely rare within the industry for a single tender car and would be a very unlikely event during the limited testing planned for the locomotive and tender. The cylinders have significant crashworthiness protection to provide safety and containment of the hydrogen in the unlikely event of an impact or other accident. From a longitudinal loading perspective the tender is designed to resist loads up to 7 times the acceleration of gravity.

The tender is equipped with several safety systems designed to cut-off the flow of hydrogen in the event of an emergency. In the event of a heat source or overpressure event, the tender has additional systems to ensure hydrogen is safely vented and the cylinders are depressurized. An illustration of the tender showing some of the external safety systems is shown in Figure 11.

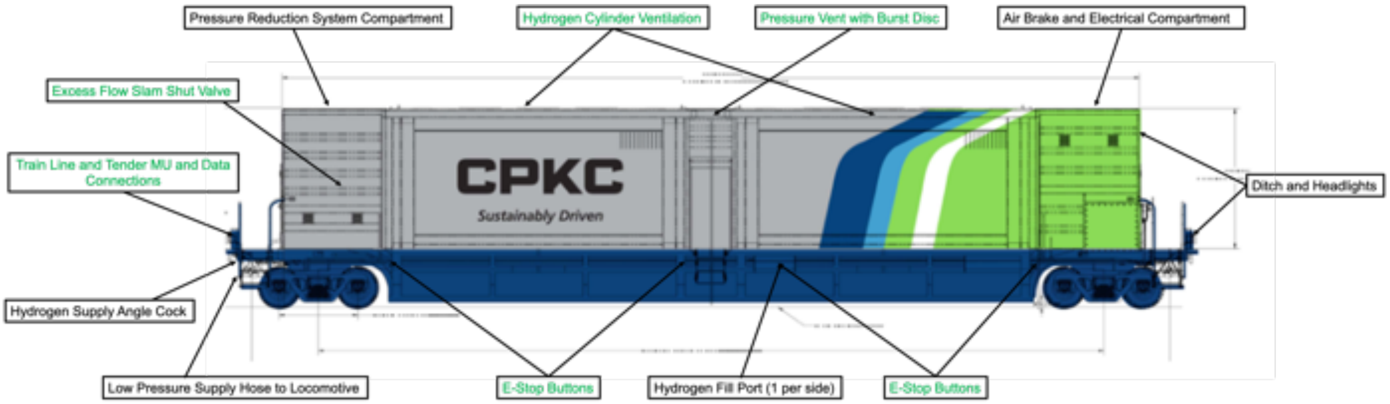

Figure 11 - Illustration of tender and safety external safety systems.

3.2.3 – Locomotive Safety Systems

Similar to the tender, the locomotive is equipped with several safety systems. These safety systems include hydrogen gas detectors and fire eye cameras. These systems are linked into CPKC's locomotive control system. An alert from these systems will safely stop locomotive operation and close all hydrogen valves. A photo of the CP 1200 and tender is shown in Figure 12.

Figure 12 - CP 1200 HHP locomotive and tender during a mainline non-revenue test.

4.0 – Locomotive In-Service Testing

Testing of the LHP CP 1002 locomotive started in CPKC's Ogden Park terminal in April 2023. The initial tests were 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 was assessed through post-testing checks. These checks are provided in Appendix A. Once initial testing and validation was completed, the CP 1002 was deployed into service on November 21st, 2023. Since November, over 25 in-service deployments were performed. Presently, the CP 1002 is deployed without a human monitoring the locomotive in real-time. The train crews who operate the locomotive using a remote-control capable locomotive simply couple onto the CP 1002, setup the unit, and start their shift. A typical shift ranges between 12 – 16 hours. All monitoring is performed remotely by the hydrogen team. No in-service failures have occurred to date. Prior to and following each test outlined in Figure 13:

- Pre and post locomotive and tender checks are performed

- Pre and post inspection checklists must be filled out by the hydrogen locomotive field technicians. A sample checklist is included in *Appendix A*.

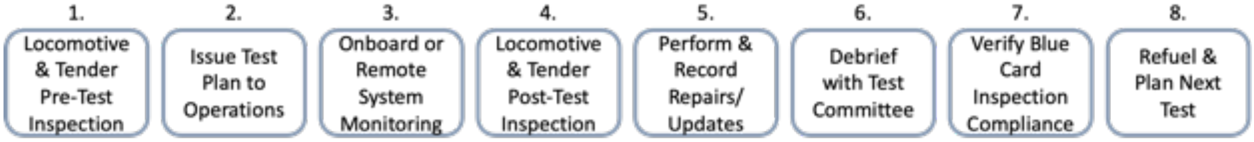

Figure 13 - Pre and Post-Test process for each test for the CP 1200 locomotive and tender.

A testing committee which includes representative from CPKC management and labour review each test and discuss the results prior to moving to the next test.

Testing of the HHP locomotive started in January 2024. Similar to the CP 1002 commissioning of individual systems and subsystems was performed followed by incremental movement testing. The focus of the CP 1200 testing is directed towards mainline operation as the intent of the locomotive is line-haul. Similar to the CP 1002 testing has progressed well and the locomotive has zero recorded in-service failures to date. Fuel cells, batteries, and associated systems perform similarly to the CP 1001 and CP 1002 as the architectures are functionally the same. The zero-emission component integration remains stable on each platform validating CPKC's design.

5.0 – Hydrogen Refueling Infrastructure

The project funding enabled CPKC to install two (2) refueling facilities. Our first fueling station was established at the Ogden campus in Calgary, followed by a second location at the Clover Bar yard in Edmonton. Additional fueling infrastructure is being rolled out in 2024 and 2025 in Lethbridge, Alberta and Golden, British Columbia as an expansion to this project.

The Calgary site shown in Figure 14 produces green hydrogen using solar electricity supplied by the CPKC Ogden campus 5MW solar farm. Green hydrogen, an environmentally friendly fuel, is generated by electrolyzing renewable electricity and water. The electricity is used to split the water (H_2O) it into hydrogen ($2H_2$) and oxygen (O_2). The Calgary and Edmonton facilities both harness municipal water supply. The produced hydrogen gas from each of these facilities is compressed and stored in cylinders, ready to refuel locomotives as needed.

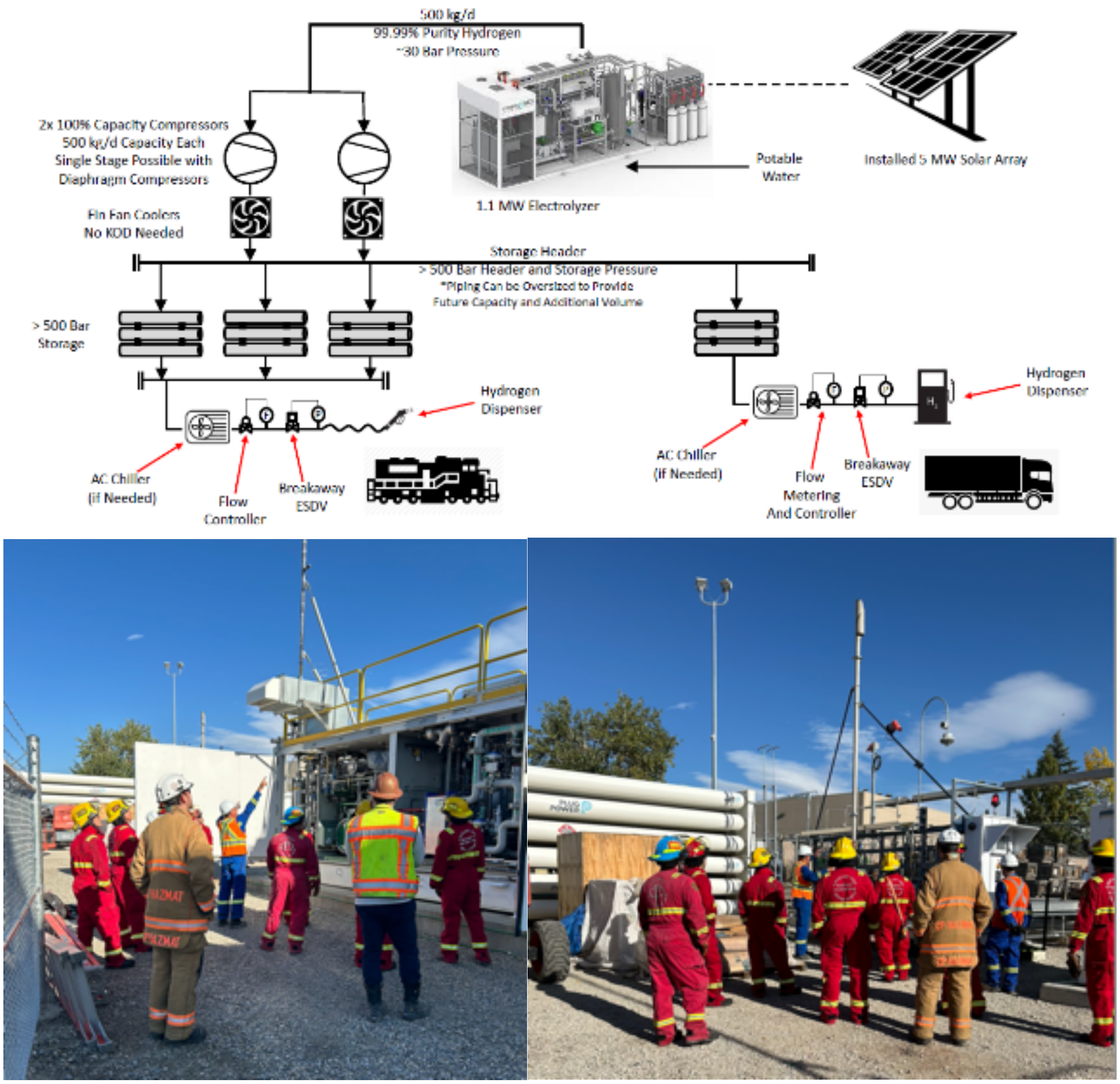

Figure 14 - CPKC/ATCO Hydrogen Production and Refueling Facility (Ogden, AB).

5.1 Direct-To-Locomotive (DTL) Refueling

As part of the project, CPKC also explored Direct-To-Locomotive (“**DTL**”) refueling capabilities. 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 directly to the locomotive or DTL via mobile fueling trucks is required and has been deployed in operation for diesel-electric locomotives. Within the context of this project, CPKC wanted to demonstrate this benefit is equally applicable to hydrogen fuel cell battery electric locomotives.

Complete DTL refueling has been achieved and demonstrated by utilizing a liquid hydrogen (“**Hydra**”) trailer. The trailer includes onboard liquid hydrogen storage which is evaporated, compressed, and dispensed directly into the locomotive. CPKC first utilized hydrogen gas trailers to perform DTL refueling. However, delivery of hydrogen through a simple hydrogen gas trailer using a pressure cascade as illustrated in Figure 15 cannot achieve complete refueling. The advantage of the Hydra trailer is that it can compress the hydrogen gas and dispense up to 350 Bar to ensure a complete fill of the locomotive(s). The Air Products Hydra trailer refueling the CP 1002 locomotive is shown in Figure 16.

Figure 15 - Certaurus hydrogen gas trailer refueling the CP 1001 via pressure cascade to demonstrate Direct-To-Locomotive ("DTL") refueling.

Figure 16 - Air Products liquid hydrogen "Hydra" trailer refueling the CP 1002 to demonstrate Direct-To-Locomotive ("DTL") refueling.

6.0 – Locomotive Results, Improvements, and Next Steps

The testing described in the previous section validates that hydrogen fuel cells and batteries can be integrated and used to drive existing locomotive electric traction motors. Performance comparable to existing diesel-electric locomotives can be achieved. CPKC practically demonstrated in-service deployment of the CP 1002 and CP 1200 locomotives in terminal and mainline revenue service. Overall feedback from operating management and train crews were positive. However, range continues to be an area of improvement. CPKC will continue to improve increasing onboard hydrogen volumes by maximizing component footprints and the overall locomotive layout.