SANDIA REPORT
SAND2025-10986
Printed September 2025

Sandia National Laboratories

Hazard and Operability Analysis for Operating, Refueling, and Maintenance of Fuel Cell Electric Buses

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ABSTRACT

Since hydrogen vehicles can be implemented in heavy-duty transportation applications such as buses, it is important to understand safety hazards and risks of hydrogen fuel cell electric bus (FCEB) and refueling technology. We conducted a hazard and operability analysis for FCEB operation/driving, refueling, and maintenance/inspection. We identified failure modes and consequences and defined a qualitative risk metric as the product of the likelihood of a failure and the severity of the worst-case consequence, ranked ordinally. We assigned risk ratings to failures to provide a qualitative comparison. Component wear, faulty monitoring equipment, and procedural errors were found to be high-priority hazards due to the possibility of hydrogen release and ignition. Safeguards like regular inspection and maintenance of equipment and facilities, procedural documentation and operator training, and implementation of monitoring equipment redundancies were recommended. These outcomes can facilitate safe development, adoption, and operation of FCEBs and identify key research areas.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Hydrogen and Fuel Cell Technologies Office (HFTO). This work was performed as part of a cooperative research and development agreement (CRADA) with the Pacific Northwest National Laboratory (PNNL) and the Port of Portland/Portland International Airport (PDX). The authors thank Dusty Brooks, Chris LaFleur, and Kristin Hertz from Sandia National Laboratories and Arun Veeramany from the Pacific Northwest National Laboratory for their technical reviews of this work.

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EXECUTIVE SUMMARY

Inclusion of hydrogen vehicles in heavy-duty vehicle fleets can support resilience and reliability of transportation systems. In the United States, hydrogen fuel cell electric passenger buses are emerging as an alternative to buses that utilize more traditional fuels and some partially converted fleets are already operational in several states including California. It is important to develop an understanding of the safety implications and potential risk and hazard mitigations for these systems as they continue to gain traction in the heavy-duty transportation sector. In this paper, we present a high-level qualitative overview of hazards, causes, and consequences for a hydrogen fuel cell electric bus (FCEB) through a hazard and operability analysis (HAZOP).

We conducted a HAZOP for three FCEB modes: operation (driving), refueling, and maintenance and inspection. Bus operation involves pressurized delivery of hydrogen from the storage tank to the fuel cell, where electricity is generated and used to power the electric traction motor of the bus. Refueling may use compressors/pumps to achieve desired flow rates or a cascading process in which the onboard tank is pressure-equilibrated with storage vessels at sequentially increasing pressures.

The main components considered in the operation (driving) HAZOP analysis include the hydrogen storage tank and its thermal pressure relief device as well as the hydrogen fuel cell, interconnecting piping, and the traction battery. Most of the components considered in the refueling hazard analysis are part of the dispenser system, which is located at the refueling station. These components include the chiller, breakaway, hose, and nozzle assembly, although interfacing components onboard the vehicle such as the fueling receptacle are also considered. The maintenance and inspection process entails procedures related to testing and replacement of FCEB subsystems and components, such as leak testing, ground integrity testing, filter replacement, and hydrogen storage tank replacement.

Several patterns emerged across these three HAZOPs. We identified that three major hazards for FCEBs and their facilities are material wear and corrosion caused by hydrogen embrittlement or other effects, malfunctioning equipment like sensors and instrumentation, and human or procedural errors during refueling, maintenance, or inspection. These hazards have the potential to cause hydrogen releases of varying magnitudes, posing risk to the rest of the vehicle and to the people in proximity to the system, depending on the scenario. The most severe outcomes or consequences of these leaks included hydrogen releases into areas of potentially high risk, such as confined or poorly ventilated spaces or areas possibly storing oxygen, generation of ignition sources from inspector or operator error such as improper grounding, and ignition of released hydrogen even in the event of proper equipment function (i.e., release of hydrogen from a thermal pressure relief device).

Safeguards against these identified hazards and consequences can significantly prevent and mitigate these risks. First, implementation of protocols for regular inspection, maintenance, repair, and replacement of components for both the FCEB and refueling station dispenser is recommended. Additionally, vehicle and dispenser station owner-operators are responsible for the maintenance of rigorous documentation and training programs for personnel involved in operations, inspections, and maintenance. Implementation of redundancies in equipment where feasible, such as using multiple sensors, can also act as a hazard mitigation by reducing the likelihood that an anomaly in the system goes undetected.

The outcomes of this HAZOP can, at a high level, inform safety protocols and procedures for bus fleet and dispenser station owner-operators. They provide a research direction and identify potential priorities for more granular quantitative analyses of hydrogen FCEB vehicle and facility hazards. These results can support the safe development and advancement of the hydrogen FCEB sector.

ACRONYMS AND TERMS

Acronym/Term	Definition
CVSA	Commercial Vehicle Safety Alliance
FCEB/V	fuel cell electric bus/vehicle
FMEA	failure modes and effects analysis
HAZOP	hazard and operability analysis
NHTSA	National Highway Traffic Safety Administration
PPE	personal protective equipment
TPRD	thermal pressure relief device

1. INTRODUCTION

Incorporating diverse alternative fuels into the transportation sector can bolster resilience and reliability [1], and heavy-duty hydrogen vehicles may play an increasing role in the coming years. Heavy-duty hydrogen vehicles including trucks, buses, and locomotives are currently in various stages of testing and deployment in the United States for use cases that include emergency response [2], public transportation [3], freight [4], and aviation and related ground operations at airports [5]. For example, the Orange County Transit Authority in California is currently committed to converting its bus fleet for public transportation to a combination of plug-in battery-electric buses and hydrogen fuel cell electric buses (FCEBs) [6]. Public fuel cell electric bus fleets have also been adopted in other parts of California including Fresno, Monterey, Oceanside, San Bernardino, Stockton, and San Diego [7]. Transit authorities in other parts of the United States have also adopted fuel cell electric bus services within the last five years, including the Stark Area Regional Transit Authority in Ohio, the U.S. Air Force at Joint Base Pearl Harbor-Hickam in Hawai'i, and the Champaign-Urbana Mass Transit District in Illinois [8]. The Port of Portland and the Portland International Airport worked on a project with the Center for Transportation and the Environment in 2023-2024 to plan for the phasing out of the airport's aging bus fleet used for transporting passengers between areas within the airport, as well as the replacement of the current natural gas buses with battery electric buses or FCEBs [9].

As these applications approach wider adoption in heavy-duty transportation, it is imperative to understand potential hazards and risks of hydrogen vehicle technology so preventive safety measures and mitigation strategies can be implemented. Some existing studies have conducted hazard and risk assessments for different aspects of hydrogen vehicles. Hoseyni et al. performed a high-level Structured What-If method and a Bowtie barrier analysis on hydrogen refueling stations, vehicles, and garages, and used the results to recommend risk mitigative actions related to enhancement of safety barriers using hardware, improvement of human performance, and refinement of the management system [10]. The National Highway Traffic Safety Administration (NHTSA) released a failure modes and effects analysis (FMEA) of hydrogen fuel cell vehicles and rated component-level failures by likelihood, consequence, and overall risk [11]. Song et al. published a quantitative risk assessment and a hazard and operability analysis (HAZOP) for the components of the hydrogen supply system, including the solenoid valves, pressure safety and regulation valves, flow and temperature transmitter, heat exchanger, flow switch, and heat exchanger in the air supply and cooling systems; this study focused on using optimized system architecture to mitigate risks [12]. Shen et al. performed a HAZOP and FMEA for onboard hydrogen fuel cell vehicles, with an emphasis on accident scenarios such as leakage and the potential resulting ignition outcomes such as combustion, deflagration, and detonation. They found that installing safety hardware like automated shut-off valves and forced ventilation and implementing emergency response safeguards like an emergency call unit could reduce medium- to high-risk events to acceptable levels [13].

In this report, we present a qualitative risk assessment in the form of a HAZOP for a fleet of FCEBs, considering three modes: driving/operation, refueling, and maintenance of the buses. Unlike the component-level qualitative risk assessments in the literature, the focus of this HAZOP is on deviations from normal or expected system behavior leading to releases of hydrogen, and, unlike the study by Shen et al., we expand the analysis to the refueling dispenser system in addition to the onboard system. We can thus consider risk in a more holistic way for multiple operational modes of the FCEB, not just driving. At a high level, we describe failure modes, suggest possible causes and outcomes, and present ideas for risk mitigative safety measures that can be implemented by different stakeholders. The focus of this assessment is on unintended hydrogen leaks and the potential resulting ignition outcomes, namely, jet fires and explosive overpressure-producing events. While this assessment focuses on buses, the findings are broad and can be used as a starting point for safety discussions of other types of hydrogen vehicles.

1.1. FCEB Hazards and Safeguards Overview

Hydrogen fuel cell vehicles have several unique hazards. This report focuses on the hazards relating to adverse outcomes, namely combustion events, that may occur from the release of hydrogen into open air.

1.1.1. Fire Hazards

Hydrogen has a flammability range between 4 and 74 vol% in air [14]. Exposure of a flammable mixture of hydrogen to an ignition source can cause either immediate ignition, resulting in a jet fire, or delayed ignition of an accumulated hydrogen mass, resulting in an explosive event like a deflagration or detonation [15]. Ignition and combustion of hydrogen can cause harm to people and built infrastructure such as the vehicle itself, refueling facilities, and garages. Hydrogen jet fires can reach temperatures of up to 1500°C [16] and radiative heat fluxes that are above accepted exposure limits for people and equipment [17]. These conditions can cause burn injuries, fatalities, structural weakening and/or thermal damage to equipment [18]. Deflagrations and detonations, which differ in flame propagation speed and resulting overpressure and impulse, can damage ears and lungs, displace people, launch debris as projectiles that may result in injury or fatality, break glass, or deform and/or weaken structural components of buildings [18].

1.1.2. Preventing Hazardous Conditions and Lowering Their Likelihood: General Best Practices for Safe FCEB Design and Operation

The general principles of designing systems or operating and maintenance protocols to mitigate these combustion hazards focus on preventing the formation of flammable gas mixtures, removing ignition sources from the areas where flammable gas mixtures may be present, and developing proper protocols for emergency response and operator safeguards like personal protective equipment (PPE).

The formation of flammable gas mixtures can be prevented by ensuring leak tightness throughout the system through regular inspection and replacement of components, installation of leak detection devices in vehicle compartments where hydrogen components like the storage tanks and fuel cell stacks are located, and the inclusion of redundant and/or manual valves that can isolate hydrogen in various parts of the system. Isolation of the vehicle's hydrogen system from potential ignition sources can be achieved through protocols and signage prohibiting smoking, hot work, and other spark-producing activities near the vehicle, especially during refueling or maintenance and inspection [14].

In the event that a combustion event does occur, protocols for emergency response by trained personnel to evacuate people, extinguish the fire, and disperse and stop the flow of hydrogen, can help reduce harm. Wearing PPE such as clothing that provides some protection from heat can also help.

One unique aspect of hydrogen vehicles is that the system integrates a hydrogen fuel cell system with an electric vehicle system, so a high voltage traction battery is co-located with hydrogen tanks and fuel cell stacks. Though failures are unlikely if batteries are installed and used properly [19], battery malfunctions may cause a cascading failure effect in the hydrogen system. For example, electrical shorts or faults may unintentionally become ignition sources near the hydrogen system [20]. More hazardous battery failures such as thermal runaway and fires may also create an environment where hydrogen components may be more likely to leak because of thermal degradation due to high temperature and pressure conditions [20]. If the temperature detected by the thermal pressure relief device (TPRD) exceeds a maximum threshold (usually 110°C [21]), the TPRD will open, and pressurized hydrogen will be released from the tank. In the case where a TPRD does not open, the tank may rupture. For these reasons, the physical proximity of the hydrogen system to the battery and electrical system on the vehicle is an important consideration for hydrogen fuel cell electric vehicle (FCEV) design, operation, and maintenance.

Many commercial FCEVs also have built-in safety features and alarms that are meant to automatically mitigate these risks and protect operators and maintenance personnel. The electrical system safety components include disconnect switches used to shut down the high voltage lines, the cut loop used as a fast way to remove the power supply from the vehicle, the manual service disconnect to isolate the high voltage of the battery from the rest of the vehicle, the battery manual service disconnect to isolate the battery from the overall electrical circuit, the torque removal button to disable the hydrogen and propulsion systems, and the isolation monitoring circuit to detect if the high voltage circuit is no longer isolated from the rest of the vehicle [14].

The hydrogen safety components include venting pipes to disperse hydrogen, the manual shut-off valve to stop the flow of hydrogen from the storage tanks to the fuel cell stacks, the thermal pressure relief device to vent hydrogen from the tank if high temperatures are detected, the pressure relief valves to relieve excess pressure from the hydrogen system, and hydrogen sensors to detect leaks and initiate a system shutdown [14]. All of these fail-safes and redundancies are meant to provide additional isolation of potential hazards, thereby lowering risk and reducing the likelihood of a severely hazardous outcome.

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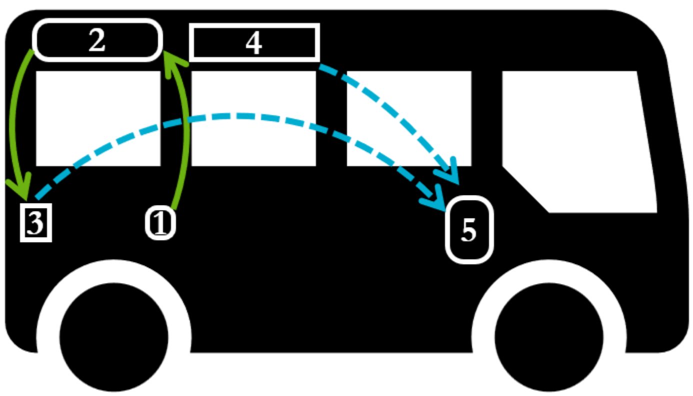
2. METHODS

2.1. System Setup

As mentioned previously, the three modes analyzed in this HAZOP are operation, refueling, and maintenance and inspection of the FCEB.

A generic schematic of the components on an FCEB is shown in **Error! Reference source not found.**; this graphic was made based on examples shown in [22] and [23]. While size and placement of the major equipment labeled on the image may vary based on the vehicle make and size, this graphic covers the main components comprised by heavy duty fuel cell electric vehicles.



Label	Component
1	Fueling receptacle
2	Hydrogen tank(s)
3	Fuel cell stack
4	Traction battery
5	Electric traction motor

Figure 2-1. Example schematic of FCEB. The green solid arrows indicate the flow of hydrogen, and the dashed blue arrows indicate the flow of electricity.

2.1.1. Operation

The vehicle is fueled with hydrogen via the fueling receptacle; the hydrogen is then stored in the hydrogen tanks until needed. During operation of the bus, the hydrogen from the tanks is sent to the fuel cell, where it is electrochemically combined with oxygen from air to generate electricity and water as a byproduct. This electricity is used in the electric traction motor to enable propulsion. An onboard traction battery or other energy storage system also provides supplemental electricity to the traction motor.

2.1.2. Refueling

Hydrogen vehicle refueling stations are generally comprised of several storage tanks at different pressures, a cooling heat exchanger (i.e., a chiller), a dispenser with a hose equipped with a hydrogen vehicle-compatible nozzle and a breakaway, and associated equipment such as pipes, valves, joints, and instrumentation. The varied hydrogen tank pressures are used for cascading fueling. According to SAE dispensing standards, the temperature of hydrogen must be maintained between -40°C and 50°C [24]. The chiller ensures the hydrogen is dispensed at -40°C to avoid a dangerous increase in temperature upon expansion of the hydrogen inside the onboard hydrogen tank due to the negative Joule-Thomson effect [25]. The breakaway is used as a fail-close valve on the dispenser in case the nozzle fails, or the vehicle driver mistakenly drives away from the station without disconnecting the nozzle from the vehicle.

Vehicle refueling requires several steps to avoid release of hydrogen into the air. The operator or person performing the refueling action must ensure that the nozzle on the refueling dispenser is securely connected to the fueling receptacle on the vehicle. Hydrogen vehicle refueling nozzles are manufactured with a visual and/or audible indicator such as a click to confirm that the nozzle has been locked onto the fueling receptacle [26]. The fueling process is controlled by the dispensing system and in some cases, the vehicle [27], [28]. Hydrogen vehicle fueling process requirements are outlined in SAE J2601 (Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles) for light-duty vehicles and [24] and SAE J2601-2 (Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles) for heavy duty vehicles [29].

Hydrogen vehicle fueling may be conducted using mechanical equipment like gaseous compressors or liquid pumps that are able to achieve a desired flow rate. Other fueling systems utilize cascading fueling processes that feature multiple stages of buffer tanks of increasing pressure. Pressure checks are conducted based on a certain amount of dispensed fuel or elapsed time to prevent overfilling of the vehicle tank or overpressurization of any of the dispenser components.

2.1.3. Maintenance and Inspection

Both maintenance and inspection processes are important to consider in risk analysis. A curriculum on hydrogen fuel cell engines published by the College of the Desert and SunLine Transit Agency contains a module on FCEB maintenance [30], [31]. This curriculum categorizes maintenance procedures as relating to the fuel cell engine (specific to FCEBs), the fuel system (specific to buses using bulk fuels like hydrogen or compressed natural gas), conventional maintenance procedures (generic to buses, with some adjustments required for fuel cell buses), and standard coach procedures (typical for all buses). This report focuses on the maintenance and inspection procedures that are specific to the fuel cell and hydrogen system.

The curriculum provides guidance on maintenance and inspection procedures based on servicing frequency. These protocols, which are shown in **Error! Reference source not found.**, include requirements for inspection, replacement, and testing of the component and system integrity.

Table 2-1. Maintenance and Inspection Procedures for Fuel Cell Engine and Fuel System – from the College of the Desert, Sunline Transit Agency, and Department of Energy [31]

Servicing Frequency or Point	Requirements for Fuel Cell Engine	Requirements for Fuel System
Daily	• Inspect resistance on ground fault monitor • Replace water or filter on ground fault monitor if necessary • Inspect fuel cell stack vent fans • Inspect water traps • Inspect air system oil detector • Inspect hydrogen diffuser	• Check burst disk vent cap
Weekly	• Leak-down test (detection of leaks anywhere in the fuel delivery circuit using pressure testing) • Check fuel cell voltage and cell voltage monitor	• Test fuel delivery circuit for leaks

Servicing Frequency or Point	Requirements for Fuel Cell Engine	Requirements for Fuel System
3750 miles	• Fuel cell external leak test (quantification of total leakage to atmosphere using flow metering) • Fuel cell transfer leak test (quantification of leakage between flow paths such as fuel-to-oxidant and fuel-to-coolant, using volumetric displacement) • Glycol system integrity test	• High-pressure circuit leak test • Motive-pressure circuit leak test • Inspect high, motive, and fuel delivery circuit components • Check roof vent caps • Check readings from fuel pressure transducer • Replace hydrogen filter
7500 miles	• Check resistance of dump chopper	• Inspect solenoid valve on motive pressure regulator
15000 miles		• Install new hydrogen storage cylinder • Conduct internal inspection of hydrogen storage cylinder • Test for ground integrity
30000 miles		• Conduct external inspection of hydrogen storage cylinder • Replace pressure regulator diaphragm, seal, and seat • Test fire suppression system

The Commercial Vehicle Safety Alliance (CVSA) also published an informational bulletin about safe inspection of hydrogen fuel cell commercial motor vehicles in 2024 [14]. This program involves ensuring that the safety features and components described in Section **Error! Reference source not found.** are present on the vehicle before starting an inspection. The bulletin also requires proper signage and labeling for parts of the entire vehicle system that can be helpful for operators, maintenance personnel, and inspectors. The signage should explicitly alert these personnel of hazards such as the presence of high voltage, corrosive and flammable materials, compressed hydrogen, venting locations, manual shutoff valves, hot liquids, and potential health hazards. This bulletin suggests that only trained personnel should be inspecting hydrogen fuel cell vehicles, and that proper PPE must always be worn during inspections. Overall, visual inspection of the vehicle should include checking for hydrogen and coolant leaks, unsecured fuel lines or electrical connectors, exposed, corroded, damaged, or unprotected wiring, and visual indications of burning, arcing, or overheating of any part of the system.

The HAZOP presented in this report for FCEB maintenance focuses on hazards that could either occur during inspection and maintenance, or that could be found and prevented through the listed inspection and maintenance procedures. Generally, it was assumed that the frequency of hazardous outcomes due to lack of inspection and maintenance is low due to established protocols, but it was also assumed that the consequence of these hazards is high because inspectors, operators, and other personnel must be close to hydrogen-containing components on the vehicle and dispenser while performing maintenance and inspection.

2.2. HAZOP

The HAZOP consisted of identifying potential deviations from normal, expected operation, whether the activity of interest was operation, refueling, or maintenance of the buses. These parameter deviations were characterized using the standard HAZOP guide words, “no,” “less,” “more,” “late,” “other,” “as well as,” “reverse,” and “part of” [32]. The guide words were used to characterize the deviation in activity of an element of the FCEB, with element being defined as either a component, process, or functionality on the vehicle or refueling facility. Possible causes and outcomes of consequence were identified for each deviation. These deviations were described in terms of specific system conditions and setpoints, with an emphasis on hydrogen system temperature, pressure, and flow rate, but also with consideration of electrical deviations of the battery system that could affect the hydrogen components.

A risk factor was calculated for the cause of each hazard or deviation from normal operation. This risk factor was calculated using the classification matrix provided in Table 2-2. The risk factor, denoted by the letter R and a number, is determined based on the frequency and consequence of the deviation. The frequency is denoted by the letter F and a number, where increasing numbers indicate higher frequencies of the cause of the deviation. The consequence is denoted by the letter C and a number, where increasing numbers indicate higher levels of harm to humans from the consequence of the hazard. The frequency and consequence numbers are defined qualitatively and are multiplied to calculate an overall risk factor. Risk numbers of 1-3 are considered low, risk numbers of 4-10 are considered moderate, and risk numbers 11-20 are considered high. While these risk numbers do not have a physical meaning, they can be used to prioritize and rank the risks of different hazards.

Table 2-2. Frequency, Consequence, and Risk Definitions Used for HAZOP Classifications

		Frequency				
		F1 Rare Occurring in exceptional circumstances	**F2 Unlikely** Occurring in few circumstances	**F3 Possible** Possibly occurring in multiple circumstances	**F4 Likely** Probably occurring in most circumstances	**F5 Almost Certain** Expected in normal circumstances
Consequence	**C1 Insignificant** No injuries or first aid required	R1	R2	R3	R4	R5
	C2 Minor Some first aid required	R2	R4	R6	R8	R10
	C3 Moderate More major injuries	R3	R6	R9	R12	R15
	C4 Severe Fatalities	R4	R8	R12	R16	R20

A frequency was assigned to a deviation based on each of its possible causes. While each hazard has multiple potential outcomes or consequences, the overall consequence number was selected based on the worst considered consequence.

These HAZOPs are qualitative, and the frequency, consequence, and the presented risk values are relative to each other and shown for comparative purposes. The outcomes presented here are based on published hazard scenarios and the engineering judgment and expertise of the authors. The purpose of these results is to provide a qualitative overview of several potential hazards related to hydrogen FCEBs and to consider potential rankings of their risks. The hazards with low-to-moderate risks should not be interpreted as being of no concern, but rather of lower relative risk than other hazards in this analysis. Similarly, moderate-to-high risks are not necessarily a high level of risk compared to other possible hazards in everyday life, but rather of higher relative risk compared to other hazards in this analysis.

Some general assumptions were used across the analyses. Material degradation resulting in hydrogen leaks was generally assigned a frequency of 3 because complete leak tightness is difficult to maintain, especially for components like heat exchangers and joints [33], [34]. The fuel cells were considered to have an even higher leak frequency because, as one source acknowledged, there is always some amount of leakage from a fuel cell, and a small amount of leakage is not as concerning or consequential as larger, more excessive leaks [31]. Additionally, operating pressures for fuel cells are on the order of hundreds of psig compared to tens of thousands of psig for the hydrogen storage system [35]), therefore presenting a lower risk. Failure of instrumentation such as sensors was assigned a frequency of 2, since we assumed it would be relatively unlikely for these devices to fail, especially if the system is inspected with proper regularity. Additionally, hazards arising from human error such as a failure to follow predetermined protocols in the operation, refueling, inspection, maintenance, or other handling of the vehicle were deemed to be rare and were assigned a frequency of 1, assuming these activities would be conducted by trained personnel rather than untrained members of the public. We used this assumption in the absence of more available data for hydrogen releases from FCEB operation, maintenance, inspection, and refueling activities and their major causes. It is possible that human error could contribute more to risk than shown in this HAZOP.

In terms of patterns in consequence assignments, outcomes involving overpressurization and/or rupture of the hydrogen tanks were given the highest severities of 4 or 5 based on the analyst's judgement of the individual situation and all discussed outcomes, since this event entails the release of hydrogen in addition to potentially creating hydrogen tank or other solid projectiles, which could cause serious harm to people. For example, for the scenario of an elevated tank temperature potentially leading to rupture of the storage tank, a severity rating of 4 was assigned, whereas for elevated traction battery temperature potentially leading to rupture of the storage tank, the severity was 5 due to the hazard associated with battery thermal runaway. Hazards related to maintenance and handling of parts of the vehicle like the hydrogen or battery system were also assigned a severity of 5 because the inspector, operator, or other person conducting these activities were assumed to be in closer proximity to the more hazardous parts of the vehicle compared to people engaging in driving and refueling activities. Smaller leaks or releases from the TPRD, which is intended for hydrogen releases (although not expected during regular operation and maintenance), were assigned lower severity levels, depending on the individual case. Most releases from the TPRD on the onboard hydrogen tank were assigned a severity level of 1, and partial hydrogen releases through smaller leaks were assigned severity levels of 2 or 3 depending on the situation. For example, material degradation over time and subsequent hydrogen leaks from the equipment was mainly assigned a severity level of 2, and full-bore leaks from components such as the refueling dispenser breakaway were assigned a severity level of 3. We also considered that the potential for ignition as an outcome may lead to higher consequences, whereas just a hydrogen release into the open air without proximity to an ignition source or confined areas may not have such severe outcomes. Analyst judgment was used to determine whether an increase in severity level may be appropriate for each failure mode based on the general likelihood of a jet fire, accumulation in a confined space followed by delayed ignition, or dispersion without ignition. Some published quantitative risk assessment models such as the Hydrogen Plus Alternative Risk Assessment Models (HyRAM+) involve assumptions that the probability of dispersion without ignition is high, and that the probability of immediate ignition (resulting in a jet fire) is higher than that of delayed ignition (resulting in an explosive event) [15]. While these values may still have uncertainty due to the unavailability of a uniform dataset and still-developing characterization of ignition events, these assumptions were used as a basis for the frequency, severity, and risk rankings used in this HAZOP.

We also use the results of the HAZOP to discuss general recommendations for safeguards against the listed hazards, as well as suggestions for the responsibilities of different stakeholders to implement these safeguards.

3. RESULTS AND DISCUSSION

The results of the HAZOP analysis are shown in the following sections. This high-level analysis covers several safety considerations for FCEB operation, refueling, and maintenance, but is not an exhaustive list of the hazards or risks associated with these activities.

3.1. Operation

The HAZOP for operation of the FCEB is shown in Table 3-1. For this HAZOP, the frequency is based on the hazard's cause and not its consequences, so it does not reflect the likelihood of, for example, a tank rupture outcome. Thus, the risk metric only accounts for consequences by assigning a number associated with the severity of the outcome (the worst-case harm that can occur). The frequency (F) multiplied by the consequence value (C) results in the risk metric (R).

Table 3-1. HAZOP Overview for Operation/Driving of the FCEB

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
1	Less	Hydrogen containment	Fuel cell leakage	Material degradation, wear, corrosion over time	• Potential ignition of leaked hydrogen • Inefficiencies / loss of fuel (economic losses)	4	2	8
2	Less	Hydrogen containment	Hydrogen storage tank leakage	Material degradation, wear, corrosion over time due to weathering and/or pressure cycling	• Potential ignition of leaked hydrogen • Inefficiencies / loss of fuel (economic losses)	3	3	9
				Sudden depressurization of hydrogen during refueling or operations leading to hydrogen migration outside of tank liner and tank liner deformation		1	4	4
3	More	Pressure	Elevated fuel cell pressure	Failure of pressure sensors	• Potential loss of fuel cell structural integrity or rupture of fuel cell membrane; mixing of hydrogen and oxygen sides; ignition outcome • Potential loss of structural integrity or rupture of fuel cell wall; mixing of hydrogen with external air; ignition outcome	2	5	10
4	More	Pressure	Elevated hydrogen storage tank pressure	Elevated tank temperatures (110°C or higher temperature surrounding the tank, such as due to a fire)	• Opening of the TPRD and emptying of tank contents to atmosphere	2	5	10

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
				Failure of pressure/temperature sensor and/or TPRD	• Potential rupture of storage tank if the TPRD does not open • Potential loss of tank structural integrity (cracking, deformation) and subsequent leaking	2	5	10
5	More	Temperature	Elevated hydrogen storage tank temperature	High temperature (110°C or higher surrounding the tank, such as due to a fire)	• Opening of the TPRD and emptying of tank contents to atmosphere • Potential rupture of storage tank • Potential loss of tank structural integrity (cracking, deformation) and subsequent leaking	1	4	4
				Failure of temperature sensor		2	4	8
6	More	Temperature	Elevated traction battery temperature	Trauma to the battery (e.g., crushing, piercing, or other impact resulting from a vehicle crash)	• Battery thermal runaway • Potential fire and/or high temperature damage to hydrogen storage tank (resulting in cracking, deformations, etc.) • Potential high-temperature-induced hydrogen tank rupture	1	5	5
				Short-circuit (e.g., from water exposure or battery wear)		1	5	5
7	More	Hydrogen Release	Unintentional hydrogen release from storage tank via TPRD	Improperly sealed, missing, or weakened vent caps	• Release and potential ignition of hydrogen when not intended • Potential hydrogen tank rupture	3	1	3
8	Other	Battery Activity	Unintentional battery gas venting	Battery thermal runaway (potentially caused by impact trauma or short-circuiting)	• Release of flammable gases such as hydrogen, carbon monoxide, hydrocarbons, and carbon dioxide and potential subsequent ignition [20]	1	4	4
9	Less	Battery Chemical Containment	Unintentional release of battery chemicals	Battery leak caused by impact trauma (e.g., vehicle crash)	• Release of potentially corrosive or otherwise-damaging gases; weakening of hydrogen tank integrity and subsequent hydrogen	1	4	4
				Battery leak caused by short-circuiting (e.g., from water penetration)		1	4	4

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
				Battery leak caused by overcharging	leakage and potential ignition	2	4	8
10	Late	Hydrogen Tank TPRD	Delayed opening of hydrogen TPRD	Failure of TRPD to open immediately and/or temperature/pressure sensor failure	• Overpressure and loss of structural integrity (cracking, deformation)	2	1	2
11	As well as	Hydrogen Tank TRPD	Ignition of hydrogen released from the TRPD	High ignition probability for TRPD hydrogen release (e.g., due to high flow rate out of TRPD)	• Hazard (to humans and equipment) caused by high-temperature, high-velocity hydrogen flame	4	1	4
				Presence of ignition source near TRPD		2	1	2

Based on the selected frequency, consequence, and risk numbers, the highest-risk hazard identified is the possibility of overheating of the hydrogen tank (labeled as causes for Nos. 4-6 in Table 3-1). The consequence of these scenarios was labeled as relatively high because of the severity of the worst-case outcome of elevated temperatures (i.e., overpressure and rupture of the hydrogen tank).

Other notably elevated risks that were characterized through this study as medium-to-high risk, included elevated fuel cell pressure due to faulty sensors (No. 3) and elevated hydrogen tank pressure from elevated temperatures or faulty pressure sensors or TRPDs (No. 4). Since the causes for these hazards were determined to occur relatively infrequently, the severe outcomes were the main contributors to the relatively high overall risk ratings.

More moderately-graded risks reflected some combination of a relatively high frequency and low consequence, low frequency and high consequence, or medium values for each. For example, No. 1 related to minor fuel cell leakage, which, as discussed, often occurs even during normal operation of the fuel cells, resulting in an assigned high frequency value. Because normally occurring leaks tend to be small, and fuel cells operate at relatively low pressures, especially compared to hydrogen storage tank pressures, the consequence of this event was relatively low. Conversely, the entry for No. 6 on high traction battery temperature leading to thermal runaway and causing high-temperature or fire damage to the hydrogen tanks was assumed to have highly severe, potentially catastrophic consequences for the hydrogen tank and hydrogen system, but likely occurs very infrequently due to the low probability of battery failure [19], resulting in a moderate overall risk rating. Similarly, the first entry for No. 5 (unexpectedly high temperatures from a fire or other anomalous event leading to storage tank overpressurization and rupture, or tank damage) was assigned a low frequency and a high consequence. An example of a hazard with a moderate risk level due to both a medium frequency and consequence is the first entry of No. 2, which is material degradation of the tank from general wear resulting in hydrogen tank leakage. Tank wear during operation of the vehicle is possible, and smaller leaks occur more frequently than larger leaks [33], [34]. This nuance is reflected in mid-level frequency, consequence, and risk assignments for the first entry of No. 2.

Several of the hazards were also considered low risk because of their relatively low frequency and consequence ratings. For example, entry No. 7 focuses on unintentional release of hydrogen from the TRPD. While any unintentional release of hydrogen is undesirable, the TRPD is designed to vent hydrogen, so it is already designed and integrated into the hydrogen system with appropriate safeguards such as orientation away from other components, equipment, or areas where people would be located during vehicle operation. Other low-risk hazards involved unintentional timing of, or ignition of hydrogen from, the TRPD. Though unlikely, these events may occur if a TRPD fails to open immediately, or if released hydrogen ignites, which may result in a high consequence outcome.

The associated recommendations for safeguards to mitigate the risks discussed in this HAZOP are provided in Table 3-2. The main safeguards relate to development of protocols for inspection, maintenance, repair, and replacement of components throughout the vehicle, implementation of redundancies in instrumentation, and compartmentalization or isolation of system components that have a high likelihood of being involved in cascading failure sequences, such as the compressed hydrogen tanks and the traction battery. Many of the actions relating to operating and maintenance protocols are the responsibility of the owner-operator of the bus or bus fleet, while other mitigations related to the vehicle design, such as incorporation of device redundancies and compartmentalization of subsystems, may be more appropriately associated with the vehicle manufacturer. Other stakeholders and involved parties like tank, sensor, and valve manufacturers or system inspectors also have a role in implementing these safeguards. However, many of these mitigations are also the joint responsibility of multiple parties. Establishing and documenting these specific contributions to safety early on in the process of forming an FCEB fleet can help improve vehicle safety robustness.

One additional notable area of risk mitigation is that of the battery system. Battery failures that lead to thermal runaway are rare if batteries are installed and operated correctly [19]. However, if a failure does occur, the battery system poses a unique challenge to the hydrogen system because it can release thermal energy and/or chemical emissions that may thermally or chemically weaken, overheat, overpressurize, and/or corrode components. If the hydrogen fuel system is affected, the TPRD may open and release the tank contents or leaking of components may result due to heat or chemical damage [20]. Sparks from the battery, such as short circuits or other electrical faults, may also act as ignition sources in close proximity to hydrogen equipment and enclosed spaces within the vehicle where hydrogen may be present in flammable concentrations. Battery thermal runaway and heating of the air around the hydrogen system may even create conditions for auto-ignition of any flammable mixture present. Effective and appropriate safeguards which help address the risk of the co-location of battery and hydrogen subsystems include battery management systems to prevent thermal runaway, TRPDs on hydrogen tanks, and emergency response protocols in the event of a battery fire and/or hydrogen release [20].

Table 3-2. Safeguards and Responsibilities for Operation/Driving

No.	Safeguard	Relevant Parties
1	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of fuel cell system (including the fuel cell stack and membrane humidifier	• Bus fleet owner-operator • Vehicle inspectors
	Installation of hydrogen sensors in fuel cell compartment	• Vehicle manufacturer
	Installation of proper venting throughout the vehicle to prevent hydrogen accumulation	• Vehicle manufacturer

No.	Safeguard	Relevant Parties
2	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of hydrogen tank	• Bus fleet owner-operator • Hydrogen tank inspectors
	Installation of proper venting throughout the vehicle to prevent hydrogen accumulation	• Vehicle manufacturer
3	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors and fuel cell stacks	• Bus fleet owner-operator • Vehicle inspectors
	Installation of redundant pressure sensors	• Vehicle manufacturer
4	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator • Vehicle inspectors
	Installation of redundant pressure sensors	• Vehicle manufacturer
5	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of temperature sensors	• Bus fleet owner-operator • Vehicle inspectors
	Installation of redundant temperature sensors	• Vehicle manufacturer
6	Implementation of battery thermal management system to detect elevated temperatures, initiate cooling, and prevent thermal runaway [36]	• Battery manufacturer
	Compartmentalization of battery and hydrogen systems onboard the vehicle	• Vehicle manufacturer
	Implementation of emergency response protocols and management in the case of vehicle crashes or other battery thermal runaway scenarios	• Bus fleet owner-operator • Vehicle inspectors
7	Regular inspection and swift replacement of missing or damaged vent caps	• Bus fleet owner-operator • Vehicle inspectors
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator • Vehicle inspectors
	Installation of redundant pressure sensors	• Vehicle manufacturer
	Installation of proper venting throughout the vehicle to prevent hydrogen accumulation	• Vehicle manufacturer
8	Installation of proper venting throughout the vehicle to prevent buildup of unintentionally released gases	• Bus fleet owner-operator
	Physical compartmentalization of battery and hydrogen system	• Vehicle manufacturer
9	Robust battery management and cell isolation system to prevent overcharging [37]	• Battery manufacturer • Vehicle manufacturer
	Installation of proper ventilation and venting throughout the vehicle to prevent buildup of unintentionally released gases	• Vehicle manufacturer
	Physical compartmentalization of battery and hydrogen system	• Vehicle manufacturer
10	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of temperature/pressure sensors and TRPD	• Hydrogen tank manufacturer • Vehicle manufacturer

No.	Safeguard	Relevant Parties
	Installation of redundant temperature/pressure sensors	• Vehicle manufacturer
11	Risk- or consequence-informed placement and setback distance adherence for hydrogen tank TRPD and exposures	• Regulatory entities • Bus fleet owner-operator
	Avoidance of co-location of ignition/spark sources with TRPD in vehicle design	• Tank manufacturer • Vehicle manufacturer
	Avoidance of co-location of ignition sources at refueling station	• Bus fleet owner-operator

3.2. Refueling

The HAZOP for refueling of the FCEB is shown below in Table 3-3.

Table 3-3. HAZOP Overview for Refueling of the FCEB

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
1	No	Hydrogen Containment	Full-bore release of hydrogen from breakaway into open air	Drive-off while refueling hose is still vehicle-connected (human error) and failure of breakaway to close	• Release of hydrogen tank contents and potential ignition of released hydrogen	1	3	3
2	No	Hydrogen Containment	Full-bore release of hydrogen from nozzle into open air	Drive-off during refueling (human error)	• Release of hydrogen tank contents and potential ignition of released hydrogen	1	2	2
				Failure of nozzle to close/stop the flow of hydrogen after refueling is complete		1	2	2
3	Late	Hydrogen containment	Full-bore release of hydrogen from nozzle into open air	Premature manual removal of nozzle from vehicle before refueling is complete (human error)	• Release of hydrogen tank contents and potential ignition of released hydrogen	2	2	4
4	Less	Hydrogen Containment	Leakage of refueling dispenser components (pipes, hoses, valves, joints, etc.)	Material degradation, wear, corrosion over time	• Partial release of hydrogen tank contents and potential ignition of released hydrogen	3	2	6
				Overpressurization of components		1	2	2
				External stressors (i.e., seismic activity)		1	2	2
5	Less					3	3	9

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
		Hydrogen containment	Onboard fueling receptacle leakage	Material degradation, wear, corrosion over time	• Partial release of hydrogen tank contents and potential ignition of released hydrogen			
				Non-leak-tight seal between fueling receptacle and nozzle (due to wear or user error)		3	3	9
6	More	Temperature	Elevated hydrogen temperature during refueling	Insufficient chilling or insulation	• Potential expansion and damage of hydrogen components (dispenser, tank, or onboard vehicle components) • Inability to maintain tank pressure leading to hydrogen release from leaking tank	2	5	10
				Inability to maintain pressure due to leak in hydrogen tank		1	5	5
				Overheating of hydrogen due to improper cascade fueling sequence (if used in that refueling system)		1	5	5
7	More	Pressure	Overpressurization / overfilling of onboard hydrogen storage tank during refueling	Failure of hydrogen tank pressure sensors	• Loss of tank structural integrity (cracking, deformation) and subsequent leaking • Rupture of hydrogen tank and subsequent leaking • Potential expansion and damage of components (dispenser, tank, or other components)	2	5	10
				Failure of hydrogen fuel level indicators		2	5	10
				Overheating of hydrogen due to improper cascade fueling sequence (if used in that refueling system)		1	5	5
8	More	Flow	Unintentionally high flow rate of hydrogen into onboard storage tank	Failure of dispenser flow meters	• Overheating of hydrogen tank, leading to overpressurization and loss of tank structural integrity (cracking, deformation) or rupture	2	5	10
10	Part of	Hydrogen tank fill	Hydrogen tank is not filled to the intended capacity	Failure of hydrogen tank pressure sensors	• No adverse consequences	2	1	2
				Failure of hydrogen fuel level indicators		2	1	2
11	No	Ground integrity	Presence of static electricity buildup	Improper grounding due to operator error		1	5	5

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
		between bus and fueling facility	in hydrogen-containing components	Improper grounding due to failures in grounding equipment	• Generation of ignition source near flammable gas mixture and possible fire if hydrogen concentration is in flammability range	2	5	10

The HAZOP for refueling is overall different from the HAZOP for operation of the FCEB, largely because, unlike the operational hazards that are mostly reliant on component failure over time, the refueling hazards are related to instrumentation failures and operator error. Some releases during refueling occur further away from the vehicle, for example if a shutoff valve doesn't close at the breakaway during a driveoff. This may allow for dispersion into the air before an adverse ignition event can happen. Additionally, refueling activities occur periodically rather than semi-continuously, unlike driving of the vehicle, so there is less time or opportunity for refueling failures to happen. Operator error, which was associated with different hazards throughout the refueling analysis, was assumed to be infrequent since operators would undergo periodic training. Operators include the refueling operators and the bus drivers; depending on the system and facility setup, the bus drivers may also perform the refueling operations, but, regardless, all involved operators would be trained. While operator errors were assigned low frequencies because of this assumption, it is important to reiterate that none of these ratings are based on quantitative data due to the lack of data on hydrogen FCEV refueling failures, and that the assigned numbers are hypothesized; a lower assigned frequency for operator error than instrumentation failure does not necessarily reflect true likelihoods. Other factors such as overwork, fatigue, shift changes, stress, and other considerations besides training may affect actual operator reliability.

The associated mitigations and safeguards for this HAZOP are shown in Table 3-4. Many of the recommended safeguards for the refueling hazards are consistent with the safeguards for the operational hazards, especially for component failures. Suggestions for improvement of safety related to refueling operator error included proper and regular training, documentation, and updating of protocols for refueling, as well as implementation of clear signage at the refueling station for both the refueling operator and the bus driver. For refueling, implementation and compliance with these safeguards is largely the responsibility of the trained station attendant, refueling operator, and owner-operator of the refueling station, who may or may not be the same entity as the owner-operator of the fleet of FCEBs. Some of the safeguards geared towards improving component reliability and robustness fall under the purview of the vehicle and/or dispenser manufacturer, although it may also be the joint responsibility of the refueling station owner-operator to ensure that appropriate safeguards are in place when purchasing, designing, constructing, and operating the refueling system. The station owner-operator is responsible for selecting, procuring, and installing reliable dispenser hardware and software.

Table 3-4. Safeguards and Responsibilities for Refueling

No.	Safeguards	Relevant Parties
1	Implementation of protocols that only allow trained operators to perform refueling tasks	• Refueling station owner-operator
	Regular/reoccurring training for refueling tasks	• Refueling station owner-operator

No.	Safeguards	Relevant Parties
	Signage to prevent drive-off	• Refueling station owner-operator
	Audible and/or visual cues on refueling interface to indicate when fueling is complete and to remind operator to return nozzle to the dispenser	• Refueling station owner-operator
2	Protocols that only allow trained operators to perform refueling tasks	• Refueling station owner-operator
	Regular/reoccurring training for refueling tasks	• Refueling station owner-operator
	Audible and/or visual cues on refueling interface to indicate when fueling is complete	• Refueling station owner-operator
	Signage to prevent drive-off	• Refueling station owner-operator • Bus fleet owner-operator
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of nozzle shut-off valve	• Refueling station owner-operator • Vehicle inspectors
3	Protocols that only allow trained operators to perform refueling tasks	• Refueling station owner-operator
	Regular/reoccurring training	• Refueling station owner-operator
	Audible and/or visual cues on refueling interface to indicate when fueling is complete	• Dispenser manufacturer (i.e., systems engineering, software/control engineering team)
4	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of refueling station components	• Refueling station owner-operator • Vehicle inspectors
	Implementation of pressure sensors and alarms	• Refueling station owner-operator
	System hardening against external stressors (e.g., pipe jacketing, protective awning over dispenser facility)	• Refueling station owner-operator • Dispenser manufacturer (i.e., systems engineering team)
5	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of fueling receptacle	• Refueling station owner-operator • Vehicle inspectors
	Protocols that only allow trained operators to perform refueling tasks	• Refueling station owner-operator
	Regular/reoccurring training	• Refueling station owner-operator
	Visual check (e.g., lock-indicating click on the nozzle when properly connected to fueling receptacle, controls that prevent commencement of refueling before a leak-tight / air-tight seal has been established)	• Vehicle manufacturer • Nozzle manufacturer • Vehicle (fueling receptacle) manufacturer • Dispenser manufacturer (i.e., systems engineering team)
	Development of pressurization / leak-tightness checks before commencement of refueling	• Dispenser manufacturer (i.e., software/control engineering team)
6	Implementation of temperature sensors and alarms on dispenser components	• Dispenser manufacturer (i.e., systems engineering team)

No.	Safeguards	Relevant Parties
		• Refueling station owner-operator
	Implementation of temperature sensors and alarms on hydrogen tanks	• Hydrogen tank manufacturer • Vehicle manufacturer • Bus fleet owner-operator
	Implementation of pressure checks before commencement of refueling to ensure that cascade refueling from dispenser is based on current onboard hydrogen tank pressure	• Dispenser manufacturer (i.e., software/control engineering team)
7	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator • Vehicle inspectors
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of level indicators	• Bus fleet owner-operator • Vehicle inspectors
	Installation of redundant fuel level indicators	• Vehicle manufacturer
	Implementation of pressure and level alarms	• Vehicle manufacturer
8	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of flow meters	• Refueling station owner-operator
	Implementation of high flow alarms	• Refueling station owner-operator • Dispenser manufacturer (i.e., software/control engineering team)
9	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of hydrogen storage/dispensing system components and conditions	• Refueling station owner-operator
	Compliance of hydrogen system vent design with safety codes and standards (e.g., API RP 521) and completion of required testing before start-up and operation	• Refueling station owner-operator • Regulatory entities (including permitting and licensing bodies)
10	Installation of tank pressure sensors and implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Tank manufacturer • Bus fleet owner-operator
	Installation of tank fuel level indicators and implementation of protocols requiring regular inspection, maintenance, repair, and replacement of level indicators	• Tank manufacturer • Bus fleet owner-operator
11	Implementation of protocols to properly ground the metal equipment in or near the hydrogen system	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols to ensure that grounding equipment is functional before use in an inspection	• Bus fleet owner-operator • Vehicle inspector

3.3. Maintenance and Inspection

The HAZOP for maintenance and inspection of the FCEB is shown below in Table 3-5.

Table 3-5. HAZOP Overview for Maintenance and Inspection of the FCEB

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
1	No	Ground integrity of metal components	Presence of static electricity buildup in metal components containing hydrogen (e.g., valves, fuel supply lines) [31]	Improper grounding due to inspector or maintenance personnel error	• Generation of ignition source near flammable gas mixture	1	5	5
				Improper grounding due to failures in grounding equipment		2	5	10
2	No/less	Venting of hydrogen from storage tank	Opening valve to hydrogen storage tank when tank is full and/or not connected to defueling venting system [31]	Inspector error (i.e., failure to defuel and depressurize system prior to maintenance and inspection)	• Potential rapid release and ignition of fuel from tank during inspection or defueling prior to maintenance	1	5	5
				Failure of pressure sensors		2	5	10
				Failure of level indicators		2	5	10
3	Other	Venting of hydrogen from storage tank	Emptying of cylinders to 0 psig without proper nitrogen/hydrogen purging [31]	Inspector error	• Potential entry of oxygen into hydrogen cylinders and development of flammable mixture [31]	1	5	5
4	No	Pressure venting of fittings under inspection	Tightening or loosening of hydrogen system fittings while system is still under pressure (e.g., during fuel circuit, motive-pressure circuit, and high-pressure circuit leak tests) [31]	Inspector error (i.e., failure to defuel and depressurize system prior to maintenance and inspection)	• Damage to hydrogen system fittings; injury and/or subsequent release and potential ignition of hydrogen	1	5	5
				Failure of pressure sensors		2	5	10
5	Other	Fuel cell leak tests	Performance of fuel cell leak test steps in an incorrect order [31]	Inspector error	• Mixing of oxygen and hydrogen from separate fuel cell compartments and potential ignition • Release of hydrogen into ambient air and potential flammable mixture formation and ignition	1	4	4
				Unclear or incomplete documentation of inspection/testing protocols		1	3	3
6	Other	Hydrogen system (fuel cell stack, membrane humidifier, other components	Usage of steam, solvents, cleaning solutions, or other chemicals for cleaning hydrogen system components [31]	Inspector error	• Long-term corrosion or wear of hydrogen components and potential future leaks • Potential exposure of hydrogen to chemicals	1	5	5
				Unclear or incomplete documentation of inspection/testing protocols		1	5	5

No.	Guide Word	Element	Deviation	Possible Causes	Consequences	F	C	R
		that convey fuel)			and reactions resulting in ignition and/or toxic gas release			
7	Other	Hydrogen storage tank exposure	Exposure of hydrogen storage tank to unapproved soaps, solvents, or other chemicals [31]	Inspector error	• Corrosion, damage, or other weakening of tank, potentially leading to leaks • Potential exposure of hydrogen to chemicals and reactions resulting in ignition and/or toxic gas release	1	5	5
				Unclear or incomplete documentation of inspection/testing protocols		1	5	5
8	No/less	Water in fuel cell engine water traps	Water traps less than half-filled with water (detected during water trap inspection) [31]	Insufficient inspection frequency	• Fuel cell gas line discharge through water outlet port (hydrogen or oxygen; if hydrogen, could lead to an ignition event)	1	4	4
9	More/ less	Fuel cell voltage	Irregular or unusual fuel cell voltages (detected during cell voltage monitor check)	Failure of fuel cell electrical components from membrane degradation [38]	• Inefficiencies in fuel cell (economic losses)	2	1	2
10	More	Fuel cell stack pressure	Excessive pressure used during fuel cell leak-down tests, internal/external leak test, and fuel-to-oxidant transfer leak test [31]	Inspector error	• Damage to fuel cell stack; enlarged leak • Potential ignition of released hydrogen	1	4	4
				Unclear or incomplete documentation of inspection/testing protocols		1	4	4
11	Less	Hydrogen diffuser fan operation	Non-operational or obstructed hydrogen diffuser fan (detected during hydrogen diffuser inspection) [31]	Freezing of vent stream water in hydrogen diffuser due to below-freezing temperatures and failure of hydrogen diffuser (e.g., failure of fan)	• Potential improper or inadequate venting and diffusion of effluent hydrogen • Increased likelihood that hydrogen concentration in the hydrogen effluent tube is above the LFL, potentially leading to an ignition event	1	5	5

Most of the maintenance and inspection hazards are related to improper use or failure of equipment, and error of the maintenance personnel or inspector. Like the refueling hazards, the likelihood of errors by maintenance and inspection personnel was assumed to be low for this analysis. Some of the highest risks identified in this HAZOP were No. 1 (the buildup of static electricity in metal components in the hydrogen system due to faulty grounding equipment), No. 2 (incomplete venting of hydrogen from the storage tank due to failure to defuel prior to maintenance and inspection and faulty pressure or level instrumentation), and No. 4 (inspection of fittings or other components while they are still pressurized with hydrogen due to faulty pressure sensors). Thus, the main contributor to maintenance and inspection risk was the small but non-zero likelihood of failure to defuel and depressurize the system, instrumentation failure, and the potential high consequence of hydrogen-pressurized component rupture and ignition of released hydrogen while an inspector or other personnel are in close proximity to the system, especially if maintenance occurs in an enclosed, inadequately ventilated space.

Some of the hazards unique to maintenance and inspection, compared to operational and refueling hazards, include entry No. 5 and 10 (deviations from proper procedures when conducting fuel cell leak tests), and entry No. 6 and 7 (use of unapproved or improper cleaning agents and chemicals that may be incompatible or damaging to the hydrogen system materials). System errors or improper configurations that can be detected during inspections include entry No. 8 (insufficient water in the fuel cell water traps), entry No. 9 (irregular voltage in the fuel cell), and entry No. 11 (malfunctioning/nonfunctioning or obstructed hydrogen diffuser). These hazards detected during inspections were assumed to have low likelihoods of occurrence, considering that inspection is designed to preventively detect these hazards, and mitigate the associated high consequences if they do happen.

The mitigations and safeguards for the FCEB maintenance activities are shown in Table 3-6. As mentioned in the CVSA bulletin, inspectors must be specifically trained to inspect hydrogen FCEVs [14]. Regular and updated training and documentation for maintenance and inspection procedures can help reduce human error, as can requiring redundancy in inspections (i.e., requiring that inspections be conducted jointly by at least two individuals). The bus fleet owner-operator is largely responsible for implementing risk mitigations for maintenance and inspection, but these actions may also involve other stakeholders such as a third-party inspecting agency and its individual inspectors.

Table 3-6. Safeguards and Responsibilities for Maintenance and Inspection

No.	Safeguards	Relevant Parties
1	Implementation of protocols to properly ground the metal equipment in or near the hydrogen system	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols to ensure that grounding equipment is functional before use in an inspection	• Bus fleet owner-operator • Vehicle inspector
2	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of level indicators	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols for proper and complete defueling and depressurizing of the hydrogen system prior to maintenance and inspection, including verifying that the system has been depressurized	• Bus fleet owner-operator • Vehicle inspector
	Protocols that only allow trained/certified inspectors to perform tasks related to and involved in equipment inspection	• Bus fleet owner-operator
	Regular/reoccurring training for inspectors	• Bus fleet owner-operator • Inspecting agency
	Protocols requiring inspections to be done in groups of two or more	• Bus fleet owner-operator

No.	Safeguards	Relevant Parties
		• Inspecting agency
3	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of level indicators	• Bus fleet owner-operator • Vehicle inspector
	Implementation of protocols for proper and complete defueling and depressurizing of the hydrogen system prior to maintenance and inspection, including verifying that the system has been depressurized	• Bus fleet owner-operator • Vehicle inspector
4	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of pressure sensors	• Bus fleet owner-operator
	Implementation of protocols for proper and complete defueling and depressurizing of the hydrogen system prior to maintenance and inspection, including verifying that the system has been depressurized	• Bus fleet owner-operator • Vehicle inspector
	Protocols that only allow trained/certified inspectors to perform tasks related to and involved in equipment inspection	• Bus fleet owner-operator
	Regular/reoccurring training for inspectors	• Bus fleet owner-operator • Inspecting agency
	Protocols requiring inspections to be done in groups of two or more	• Bus fleet owner-operator • Inspecting agency
5	Implementation of protocols for proper and complete defueling and depressurizing of the hydrogen system prior to maintenance and inspection, including verifying that the system has been depressurized	• Bus fleet owner-operator • Vehicle inspector
	Regular/reoccurring training for inspectors	• Bus fleet owner-operator • Inspecting agency
	Protocols requiring inspections to be done in groups of two or more	• Bus fleet owner-operator • Inspecting agency
	Proper documentation, regular review, and regular updating of inspection/testing protocols	• Bus fleet owner-operator • Inspecting agency
6	Implement protocols to use a dry or damp cloth and/or manufacturer-approved cleaning solutions for cleaning hydrogen system components	• Bus fleet owner-operator • Inspecting agency • Vehicle inspector
	Provide clear and accessible documentation	• Bus fleet owner-operator
	Provide training to operators, inspectors, and other personnel who will be performing maintenance activities	• Bus fleet owner-operator • Inspecting agency
7	Regular/reoccurring training for inspectors	• Bus fleet owner-operator • Inspecting agency
	Protocols requiring inspections to be done in groups of two or more	• Bus fleet owner-operator • Inspecting agency

No.	Safeguards	Relevant Parties
	Proper documentation, regular review, and regular updating of inspection/testing protocols	• Bus fleet owner-operator • Inspecting agency
8	Implement protocols to ensure that inspections occur with sufficient frequency to prevent water trap levels from getting too low	• Bus fleet owner-operator • Inspecting agency
9	Implement protocols to ensure that inspections occur with sufficient frequency to detect fuel cell failure early	• Bus fleet owner-operator • Inspecting agency
	Implementation of protocols requiring regular inspection, maintenance, repair, and replacement of overall fuel cell	• Bus fleet owner-operator • Inspecting agency
10	Provide training to operators, inspectors, and other personnel who will be performing maintenance activities	• Bus fleet owner-operator • Inspecting agency
	Proper documentation, regular review, and regular updating of inspection/testing protocols	• Bus fleet owner-operator • Inspecting agency
11	Implement protocols to ensure that inspections occur with sufficient frequency to detect hydrogen diffuser component failure early on	• Bus fleet owner-operator • Inspecting agency

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4. CONCLUSIONS

HAZOP analyses can provide a high-level overview of potential risks to consider early on in the design, construction, or operation of a system such as an FCEB fleet or refueling station. In this report, HAZOP analyses were conducted for operation, refueling, and maintenance of a hydrogen FCEB. Overall, the main identified failures or hazards across these three modes included

- Material wear or corrosion in hydrogen-containing equipment, resulting in ignitable hydrogen leaks of varying sizes,
- Faulty equipment like sensors and instrumentation, resulting in pressures, temperatures, or hydrogen levels in equipment outside of the allowable ranges, and potentially leading to outcomes such as leaks, release of the hydrogen tank contents, and tank or component ruptures.
- Human error during refueling or maintenance and inspection, resulting in improper repair and replacement of components, or exposures of hydrogen equipment to incompatible chemicals, unallowable pressures, and static electricity buildup (i.e., an ignition source). These scenarios can lead to potentially high-risk situations while a person is in close proximity to the system. While human failures were assumed to occur at a relatively low frequency due to suggested training requirements for operators, inspectors, and maintenance personnel, the hazards in the event that the failures do occur are expected to be relatively high.

The most severe consequences found in these three HAZOPS included

- Hydrogen releases into poorly ventilated and/or confined areas (such as maintenance facilities) or areas where oxygen may be present (such as within the fuel cell or outside air), possibly resulting in a flammable gas mixture,
- Generation of an ignition source (such as static electricity from improper/incomplete grounding) near hydrogen equipment, and
- Ignition of released hydrogen into either a jet flame, deflagration, or detonation, resulting in potential harm to people and nearby infrastructure.

The main safeguards discussed across the analyses included

- Implementation of protocols for regular inspection, maintenance, repair, and replacement of components throughout the FCEB and refueling dispenser,
- Proper, regulation-compliant documentation, training, and certification for operators, inspectors, and maintenance personnel, and
- Implementation of redundancies where possible, including in equipment (e.g., instrumentation) and inspections (e.g., number of inspectors).

These analyses can be used to inform safe design of these systems as well as their associated protocols for operation, maintenance, and inspection. While not a stand-in for a full quantitative assessment, the presented HAZOP results highlight several risks that may be further examined and analyzed in more in-depth risk assessments that may follow.

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REFERENCES

[1] C. R. Johnson, "Fuel Diversification to Improve Transportation Resilience: A Backgrounder," presented at the Transportation Fuel Resilience in Tampa Bay Workshop, Mar. 25, 2019. [Online]. Available: https://www.osti.gov/biblio/1526202

[2] "Hydrogen-Powered Heavy-Duty Truck Establishes New Threshold by Traveling 1,800 Miles on a Single Fill," U.S. Department of Energy. [Online]. Available: https://www.energy.gov/eere/fuelcells/articles/hydrogen-powered-heavy-duty-truck-establishes-new-threshold-traveling-0

[3] "OCTA Invests $77.5 Million in Eco-Friendly Public Transit: Acquires 40 Hydrogen-Fuel Cell Buses," Fuel Cell Works. [Online]. Available: https://fuelcellsworks.com/2024/11/29/green-investment/octa-invests-77-5-million-in-eco-friendly-public-transit-acquires-40-hydrogen-fuel-cell-buses

[4] "CSX Unveils Its First Hydrogen-Powered Locomotive in Collaboration with CPKC," CSX. [Online]. Available: https://www.csx.com/index.cfm/about-us/csx-unveils-its-first-hydrogen-powered-locomotive-in-collaboration-with-cpkc/

[5] "Delta joins ATL, Airbus, Plug Power in hydrogen fuel study," Delta News Hub. [Online]. Available: https://news.delta.com/delta-joins-atl-airbus-plug-power-hydrogen-fuel-study

[6] "Zero-Emission Bus Program," Orange County Transit Authority. [Online]. Available: https://www.octa.net/about/about-octa/environmental-sustainability/zero-emission-bus-program/

[7] "Fuel Cell Electric Bus Deployment in California." California Air Resources Board, Oct. 20, 2022. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2022-10/FCEB-Deployment-Map.pdf

[8] L. Eudy and M. Post, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020," National Renewable Energy Laboratory, NREL/TP-5400-75583, Mar. 2021. [Online]. Available: https://doi.org/10.2172/1772437

[9] "Port of Portland Airport Shuttle Bus Fleet Conversion," Center for Transportation and the Environment. [Online]. Available: https://cte.tv/projects/port-of-portland-airport-shuttle-bus-fleet-conversion

[10] S. Mojtaba Hoseyni, M. O. Mesbah Mostafa, and J. Cordiner, "Mitigating risks in hydrogen-powered transportation: A comprehensive risk assessment for hydrogen refuelling stations, vehicles, and garages," *International Journal of Hydrogen Energy*, vol. 91, pp. 1025–1044, Nov. 2024, doi: 10.1016/j.ijhydene.2024.10.074.

[11] D. Stephens, S. Rose, S. Flamberg, S. Ricci, and P. George, "Failure Modes and Effects Analysis for Hydrogen Fuel Cell Vehicles - Subtask 1," U.S. Department of Transportation: National Highway Traffic Safety Administration, DOT HS 811 075, Feb. 2009. [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.gov/files/811075_0.pdf

[12] K. Song, R. Jia, P. Huang, X. Huang, B. Zhang, and F. Li, "Functional safety-oriented hazard analysis and risk assessment for vehicular fuel cell systems," *Heliyon*, vol. 11, no. 1, Jan. 2025, doi: 10.1016/j.heliyon.2024.e41410.

[13] Y. Shen, H. Lv, Y. Hu, J. Li, H. Lan, and C. Zhang, "Preliminary hazard identification for qualitative risk assessment on onboard hydrogen storage and supply systems of hydrogen fuel cell vehicles," *Renewable Energy*, vol. 212, pp. 834–854, May 2023, doi: 10.1016/j.renene.2023.05.037.

[14] "2024-02 - Hydrogen Fuel Cell Commercial Motor Vehicle Inspections." Commercial Vehicle Safety Alliance, Sep. 12, 2024. [Online]. Available: https://www.cvsa.org/wp-content/uploads/2024-02-Inspection-Bulletin.pdf

[15] B. Ehrhart, E. Hecht, and B. Schroeder, "Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual," Sandia National Laboratories, SAND2023-14224, Dec. 2023. [Online]. Available: https://doi.org/10.2172/2369637
[16] W. Liu, F. Markert, L. Giuliani, and S. Hostikka, "Analyzing the gas temperature of a hydrogen jet fire in a compartment with the Fire Dynamics Simulator," *International Journal of Hydrogen Energy*, vol. 53, pp. 1097–1106, Jan. 2024, doi: 10.1016/j.ijhydene.2023.11.306.
[17] NFPA 2, "Hydrogen Technologies Code." National Fire Protection Association, 2023.
[18] The Netherlands Organisation of Applied Scientific Research, *Methods for the determination of possible damage to people and objects resulting from release of hazardous materials*. 1989.
[19] R. Shen, Y. Quan, J. D. McIntosh, A. Salem, and Q. Wang, "Fire Safety of Battery Electric Vehicles: Hazard Identification, Detection, and Mitigation," *SAE International Journal of Electrified Vehicles*, vol. 13, no. 3, pp. 279–294, 2024, doi: 10.4271/14-13-03-0024.
[20] B. Wofford, M. Louie, and M. Miletic, "Safety Hazards of Batteries and Hydrogen Tanks in Proximity," Sandia National Laboratories, Publication in Progress.
[21] H. Hussein, S. Brennan, and V. Molkov, "Hydrogen Jet Fire from a Thermally Activated Pressure Relief Device (TPRD) from Onboard Storage in a Naturally Ventilated Covered Car Park," *Hydrogen*, vol. 2, no. 3, pp. 343–361, 2021, doi: 10.3390/hydrogen2030018.
[22] "How Do Fuel Cell Electric Vehicles Work Using Hydrogen?," U.S. Department of Energy Alternative Fuels Data Center. [Online]. Available: https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work
[23] "xcelsior Charge FC." New Flyer. [Online]. Available: https://www.newflyer.com/site-content/uploads/2024/07/Xcelsior-CHARGE-FC-Brochure.pdf
[24] SAE J2601_202005, "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles," 2020. doi: 10.4271/J2601_202005.
[25] M. Genovese, V. Cigolotti, E. Jannelli, and P. Fragiacomo, "Hydrogen Refueling Process: Theory, Modeling, and In-Force Applications," *Energies: Advances in Hydrogen Energy II*, vol. 16, no. 6, p. 2890, Mar. 2023, doi: 10.3390/en16062890.
[26] "What Do You Need to Know About Hydrogen Fueling Operations?" California Fuel Cell Partnership. [Online]. Available: https://h2fcp.org/sites/default/files/Stations-Fact-sheet3_0.pdf
[27] SAE J2799_202406, "Hydrogen Surface Vehicle to Station Communications Hardware and Software," 2024. doi: 10.4271/J2799_202406.
[28] SAE J2600_201510, "Compressed Hydrogen Surface Vehicle Fueling Connection Devices," 2015. doi: 10.4271/J2600_201510.
[29] "J2601/2_201409: Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles - SAE International." Accessed: Dec. 04, 2023. [Online]. Available: https://www.sae.org/standards/content/j2601/2_201409/
[30] A. Lanz, J. Heffel, and C. Messer, "Hydrogen Fuel Cell Engines and Related Technologies: Rev 0." College of the Desert, Dec. 2001. [Online]. Available: https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm00r0.pdf
[31] A. Lanz, J. Heffel, and C. Messer, "Module 7: Fuel Cell Bus Maintenance." College of the Desert, Dec. 2001. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/03/f12/fcm07r0.pdf
[32] Risk Management Working Group Manufacturing Technology Committee, "Risk Management Training Guides: Hazard & Operability Analysis (HAZOP)." Product Quality Research Institute. [Online]. Available: https://pqri.org/wp-content/uploads/2015/08/pdf/HAZOP_Training_Guide.pdf

[33] D. Brooks, A. Glover, and B. Ehrhart, “Compressed Natural Gas Component Leak Frequency Estimation,” Sandia National Laboratories, SAND2022-14164, Oct. 2022. [Online]. Available: https://doi.org/10.2172/1892133

[34] D. Brooks and B. D. Ehrhart, “LPG Component Leak Frequency Estimation,” Sandia National Laboratories, Albuquerque, New Mexico, SAND2023-05818, 2023. [Online]. Available: https://doi.org/10.2172/2369639

[35] G. Singer, R. Köll, L. Aichhorn, P. Pertl, and A. Trattner, “Utilizing hydrogen pressure energy by expansion machines – PEM fuel cells in mobile and other potential applications,” *Applied Energy*, vol. 343, p. 121056, Aug. 2023, doi: 10.1016/j.apenergy.2023.121056.

[36] S. Chavan *et al.*, “Thermal runaway and mitigation strategies for electric vehicle lithium-ion batteries using battery cooling approach: A review of the current status and challenges,” *Journal of Energy Storage*, vol. 72, no. D, p. 108569, Nov. 2023, doi: 10.1016/j.est.2023.108569.

[37] S. More, S. Mane, S. Nangare, O. Suryawanshi, A. Swant, and S. Phalke, “EV Battery Protection from Over Charging & Over Temperature,” *International Journal of Science, Engineering and Technology*, vol. 12, no. 2, 2024, doi: 10.61463/ijset.vol.12.issue2.141.

[38] Y. P. Patil, W. L. Jarrett, and K. A. Mauritz, “Deterioration of mechanical properties: A cause for fuel cell membrane failure,” *Journal of Membrane Science*, vol. 356, no. 1–2, pp. 7–13, Jul. 2010, doi: 10.1016/j.memsci.2010.02.060.

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