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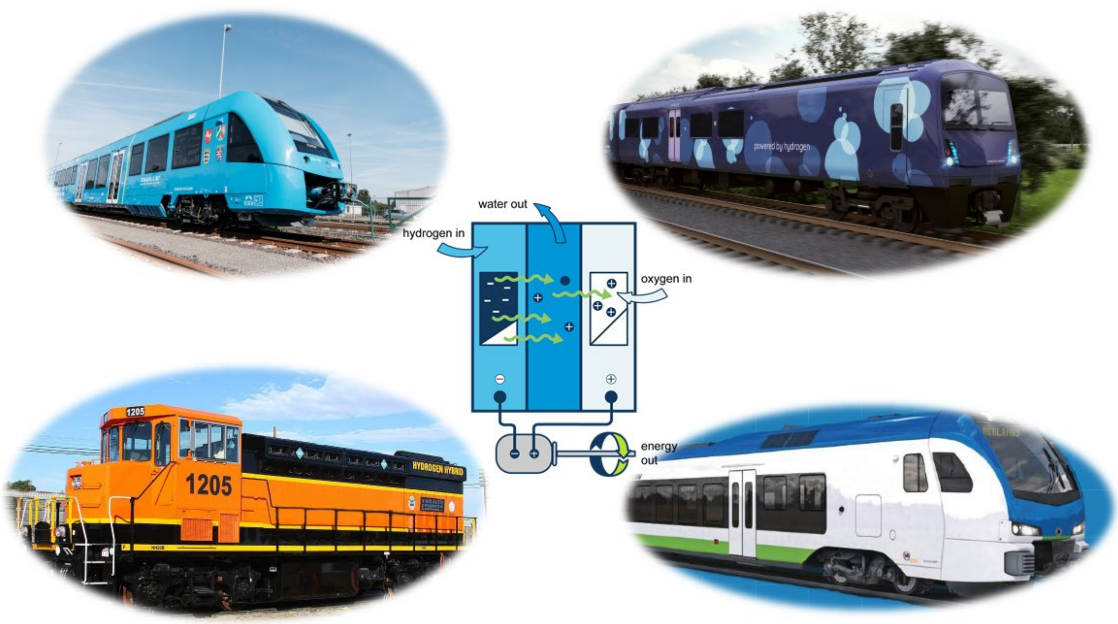
Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards



DOT/FRA/ORD-21/20

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14. ABSTRACT
Alternatives to conventional diesel electric propulsion are currently of interest to rail operators. In the U.S., smaller railroads have implemented natural gas and other railroads are exploring hydrogen technology as a cleaner alternative to diesel. Diesel, battery, hydrogen fuel cell, or track electrification all have trade-offs for operations, economics, safety, and public acceptability. A framework to compare different technologies for specific applications is useful to optimize the desired results. Standards from the Association of American Railroads (AAR) and other industry best practices were reviewed for applicability with hydrogen fuel cell technology. Some technical gaps relate to the physical properties of hydrogen, such as embrittlement of metals, invisible flames, and low liquid temperatures. A reassessment of material selection, leak/flame detection, and thermal insulation methods is required. Hydrogen is less dense and diffuses more easily than natural gas, and liquid hydrogen is colder than liquefied natural gas. Different densities between natural gas and hydrogen require modifications to tank designs and flow rates. Leaked hydrogen will rise rather than pool on the ground like diesel, requiring a modification to the location of hydrogen tanks on rolling stock. Finally, the vibration and shock experienced in the rail environment is higher than light-duty vehicles and stationary applications for which current fuel cell technology has been developed, requiring a modification in tank design requirements and testing.

15. SUBJECT TERMS
Hydrogen, alternative fuel, fuel cell, rail car, propulsion, rail, rolling stock, railroad

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

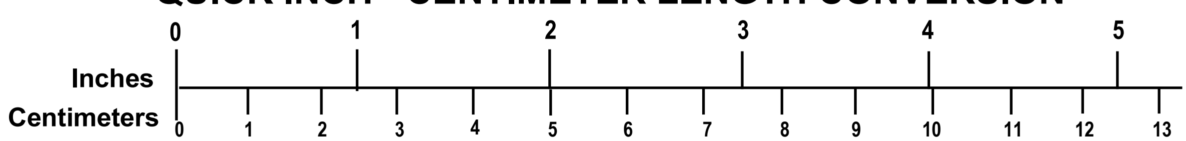
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

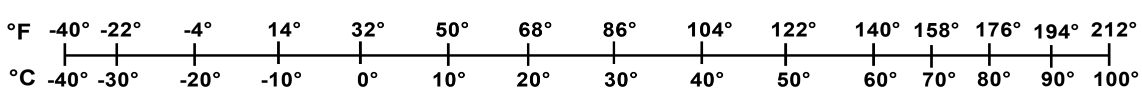
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Contents

Illustrations

Executive Summary

The Federal Railroad Administration sponsored research to evaluate the safety, applicability, and effectiveness of alternative fuel strategies for rail transportation. Sandia National Laboratories conducted this research in Albuquerque, NM, and Livermore, CA, from September 2018 to March 2021. There are multiple alternative fuel options to achieve low-emission train operation relative to current diesel technologies. These include electrified track, battery electric locomotives, and hydrogen fuel cells. Different technologies may be better suited to a specific type of rail application (e.g., long-haul freight vs. regional passenger rail vs. yard operations). The selection of a technology is based on multiple factors, such as economics, environmental impacts, safety hazards, and public acceptability. How well a specific propulsion technology matches up to a specific application will inform how much of an impact the new technologies could make for that application. Current diesel fueled locomotives as well as new battery electric, hydrogen fuel cell, or electrified track scenarios all have trade-offs in terms of operations, economics, safety, and public acceptability. One technology is not necessarily going to be best in all situations, and so a framework to compare different technology options for specific applications is useful to fully optimize the desired results. This report describes one such framework, an impact figure of merit, that combines factors from five different categories: economics, environmental, safety, performance, and public acceptability—to evaluate the technology-application compatibility.

The research team reviewed several standards from the Association of American Railroads (AAR) Manual of Standards and Recommended Practices (MSRP) for applicability with hydrogen fuel cell technology and identified gaps in these requirements. Some of the significant potential gaps in the current standards for use in hydrogen relate to the physical properties of hydrogen and how those properties can differ from diesel or natural gas fuels. Hydrogen is a flammable, non-toxic gas at room temperature that is lighter than air. The only product when hydrogen is burned or consumed in a fuel cell is water. Unique characteristics of hydrogen such as embrittlement of some metals, invisible flames, and very low liquid temperatures are reasons to reassess current requirements for the introduction of this new fuel source.

Overall, the current industry strategy for the safe implementation of compressed natural gas (CNG) or liquefied natural gas (LNG) is directly applicable for establishing on-board fuel storage of gaseous hydrogen (GH_2) or liquid hydrogen (LH_2), with some revision in the implementation details. While both hydrogen and natural gas are flammable lighter-than-air gases that can be stored as a compressed gas or cryogenic liquid, their physical properties are different. Hydrogen is less dense and diffuses more easily than natural gas, and LH_2 is colder than LNG. These properties directly affect both operational and safety procedures. For example, LNG tanks can be purged with nitrogen to remove oxygen before use; however, because the colder LH_2 can liquefy and freeze nitrogen, a different purge gas (e.g., hydrogen itself) must be used. The differences in density means that tanks sizes and flow rates will also be different, which will affect car design and refueling requirements. The current 300 gallons per minute (gpm) flowrate for diesel or 400 gpm flowrate for LNG may not be directly applicable to hydrogen (GH_2 or LH_2). This may affect refueling times, on-board storage tank sizes, and whether or not a tender is needed (depending on the application).

Different tank design and insulation requirements will be needed for LH_2; for example, current requirements for access to the inner LNG tank for inspection purposes might not be practical for

LH_2 tanks that need to maintain colder temperatures. Hydrogen leaks and ignited flames can be invisible in daylight with low levels of radiant heat. There is a need for specialized detection methods to monitor containment of hydrogen on board and in storage areas. Finally, hydrogen can embrittle certain metals and so any storage vessel design needs to account for this effect. Hydrogen embrittlement is caused by the diffusion of hydrogen into the metal itself and interacting with constituents in the alloy, which can reduce mechanical properties such as fracture toughness. Selection of specific stainless steel alloys for hydrogen storage will be critical for rail designs. Stainless steel is less susceptible to degradation upon hydrogen exposure, in comparison to other metals. In addition to material selection, design practices can also mitigate this concern, such as increased wall thickness and specific welding techniques for tank connections.

There are also gaps in AAR MSRP requirements related to the rolling-stock car design (i.e., locomotive, tender, or tank cars) with the use of hydrogen. Ventilation is critically important for the safe use of a flammable gas in an enclosed space because ventilation dilutes the gas to safe concentrations. Current restrictions on active ventilation for electronics within the AAR MSRP are likely not applicable to hydrogen systems. There is also some ambiguity in whether spaces are passively vented or actively ventilated, and what specific concentration values are to be used for alarms and shutdowns. Even if concentrations are specified as fractions of the lower flammability limit (LFL) or lower explosive limit (LEL), the actual concentration value should be stated explicitly to remove ambiguity. Furthermore, gaseous hydrogen tanks need to contain high-pressure GH_2 (up to 700 bar) or liquid hydrogen tanks need to limit heat ingress into a very cold (20 K) supply of LH_2. Hydrogen leaks tend to rise up in air rather than pooling on the ground like diesel, meaning that if the location of the tanks are at the bottom of cars the hydrogen could accumulate in the car itself and cause safety hazards. Hydrogen fuel cell powered locomotives would not operate in a dual-fuel powered combustion engine like natural gas, and so would require an entirely new design of locomotive. Therefore, if hydrogen is to be used and stored onboard a locomotive, new standards or requirements will need to be written for tanks to be located near the top of rail cars or include other design features to prevent accumulation, rather than diesel tanks which can be located beneath the underframe. Finally, the vibration and shock experienced in the rail environment is significantly higher than current hydrogen fuel cell applications, such as light-duty vehicles and stationary applications. This makes vibration testing on all aspects of hydrogen fuel cell systems critically important, including the electronics in the fuel cell system, fuel storage tanks, pipes, and connections. If LH_2 is involved, vibration testing will need to be conducted at the cryogenic temperatures that the equipment will experience in operation.

Hydrogen, like other fuels, has unique physical properties and hazards, and it must be assessed and regulated according to these physical properties to ensure safe operation in a new application. Hydrogen fuel cells have the potential to introduce significant emission reductions across the United States via zero-emission transportation operations while eliminating toxic spills in the environment. Fuel cell locomotives do not require track modifications and can refuel in a similar timeframe to diesel locomotives. Current rail standards and regulations will need to be developed or modified to address high pressure GH_2 and cryogenic LH_2 storage, tank design, fueling stations, safety procedures, and training of personnel. Identification of these gaps allows for additional investigations into these topics to allow the safe deployment of hydrogen fuel cell technology in the rail environment.

1. Introduction

This report presents the results of research performed between September 2018 and March 2021 by Sandia National Laboratories, under contract by the Federal Railroad Administration (FRA), to review the potential impact of hydrogen fuel cell technology on various rail applications and assess current rail design and safety standards for applicability to hydrogen. This report summarizes project activities, objectives, scope, and findings of the standards review. The research team provides recommendations for addressing identified gaps for the use of hydrogen in rail applications.

1.1 Background

FRA promotes and enforces the U.S. Department of Transportation's (DOT) strategic goals of safety through activities that seek to assess and ensure that new technologies such as hydrogen and fuel cell technologies for locomotives do not compromise public safety or the public rail infrastructure. As a result, FRA contracted Sandia National Laboratories to analyze the availability, feasibility, and safety of hydrogen and fuel cells for rail applications. This collaborative partnership will help FRA develop a greater understanding of the potential of the technology to improve efficiency and safety in the rail industry. The results from this research will help inform future revisions of industry standards and Federal regulations development, as well as inform design and operational decisions.

1.2 Objectives

The objectives of this project were to:

- Assess the potential tradeoffs for hydrogen fuel cells for various rail applications (including freight, passenger, and switcher locomotives) compared to other zero-emission technologies such as battery electric locomotives or electrified track (catenary)
- Assess current rail safety and design standards, currently written with a focus on diesel or natural gas fuel, for applicability for hydrogen. Specifically, identifying gaps in the current standards and similar requirements or best practices from other hydrogen industries as potential ways to address these gaps.

1.3 Overall Approach

The research team conducted a literature survey to identify tradeoffs and other examples where hydrogen fuel cell technology was used in applications similar to rail. The research team formulated and demonstrated a quantitative framework to assess multiple potential technologies and applications. Next, an assessment took place of current rail standards to identify specific requirements that would need to be modified to accommodate hydrogen use. These gaps were discussed internally with experts in hydrogen research and informed by discussions with FRA as well as hydrogen experts in industry to clarify applicability and how to address the gaps.

1.4 Scope

The research team developed an impact framework to compare the baseline diesel fuel with battery electric, electric track, GH_2 fuel cell, and LH_2 fuel cell locomotive options applied to freight, passenger, and switcher locomotive applications based on economic value, environmental impact, safety, performance, and public acceptance considerations. The category of freight locomotive was categorized as a single entity omitting subcategories such as short-haul and long-haul, and the passenger locomotive category includes both a single driving locomotive and multiple units. This framework is intended for use as a general overview of tradeoffs, not to perform a full conclusive assessment on a particular route or project.

For the assessment of rail standards, the Association of American Railroads (AAR) Manuals of Standards and Recommend Practices (MSRP) were the main focus of the review. These standards include specific design requirements and more detailed safety measures.

1.5 Organization of the Report

There are four sections and an appendix in this report. Section 1 introduces an overview of the background, objectives, approach, and scope of the project. Section 2 describes an impact figure of merit framework, as well as the tradeoffs that may be relevant for different rail applications when considering different zero-emission technologies. Section 3 provides detailed reviews of three major rail standards, and the hydrogen gaps identified in each. It also includes a discussion of the broad categories of gaps, in addition to the detailed assessment of specific requirements in each document. Section 4 provides a summary of the main conclusions of these gaps and how they might be addressed. Appendix A provides an example of the quantitative figure of merit calculations, using emissions calculations as that example.

2. Impact Figure of Merit

To assess the feasibility of transitioning a portion or all the rail industry from diesel to a hydrogen fuel-based system, the needs of the stakeholders need to be identified. To identify key strategic priority areas of Class I railway companies,[1] the research team reviewed published annual financial reports were reviewed for each company (Amtrak, 2018) (Burlington Northern Santa Fe Railway, 2018) (CSX, 2018) (Canadian National Railway, 2018) (Canadian Pacific Railway, 2018) (Kansas City Southern, 2018) (Norfolk Southern, 2018) (Union Pacific, 2019). Figure 1 provided the tallied number of companies that mentioned a similar topic as a noteworthy opportunity or risk area to key investors in a rank-ordered Pareto chart.

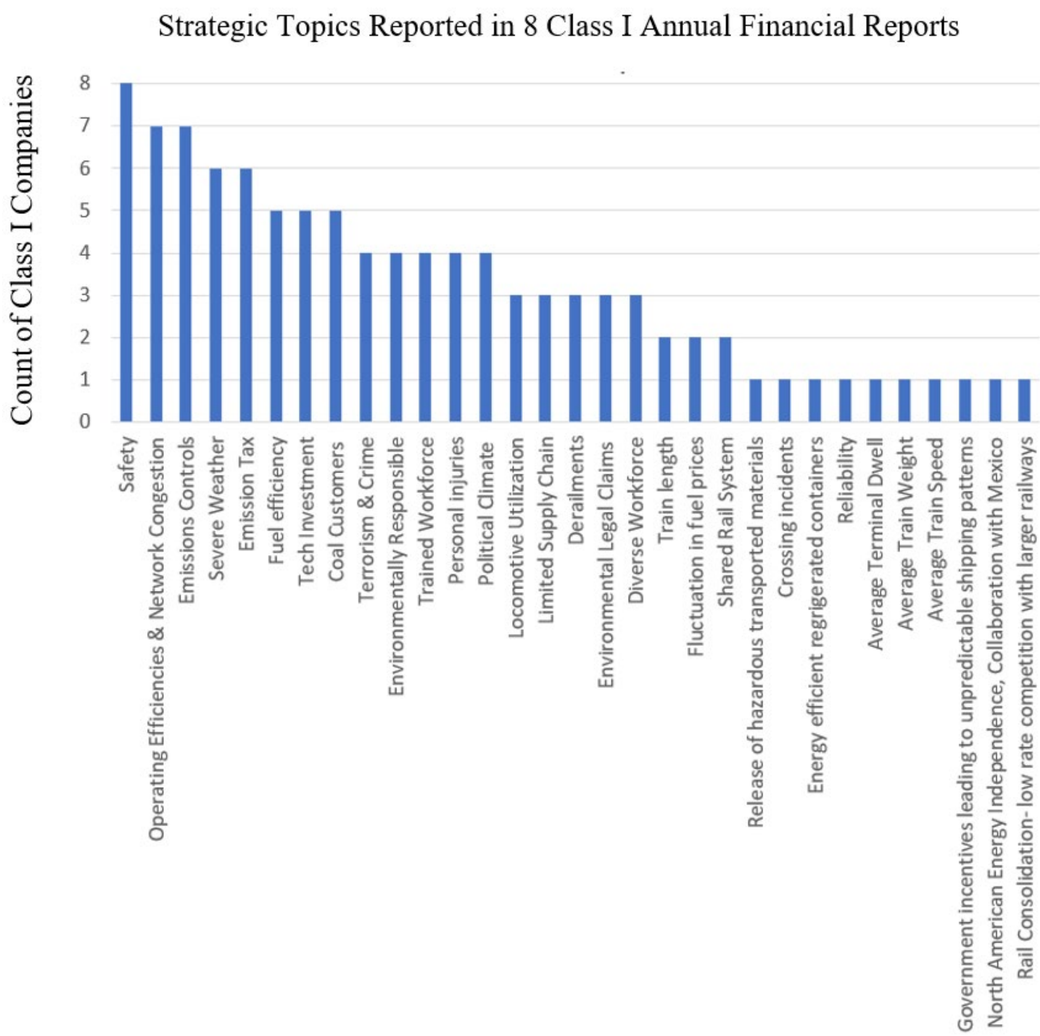

Figure 1: Pareto chart of railroad company priorities from financial reports

Interestingly, many of the most frequently mentioned strategic areas of interest are directly related to fuel and environmental concerns. Out of the eight companies considered, seven of

[1] Burlington Northern Santa Fe Railway (BNSF), Canadian National Railway (CN), Canadian Pacific Railway (CP), CSX, Kansas City Southern Railway (KCS), Norfolk Southern (NS), Union Pacific Railway (UP), and Amtrak

eight companies mentioned Emissions Controls, six of eight companies mentioned potential changes to Emissions Taxes, and four of eight companies mentioned being Environmentally Responsible. It is interesting to note that emissions controls (seven of eight companies) are more frequently mentioned than fuel efficiency (five of eight companies).

There are multiple ways to achieve low-emission train operation relative to current diesel technologies. These can include electric track (e.g., catenary or third-rail), battery electric, or hydrogen fuel cell powered by either gaseous hydrogen (GH_2) or liquid hydrogen (LH_2). Different technologies may be better suited to different types of rail applications, e.g., long-haul freight vs. regional passenger rail vs. switcher yards. Additionally, different technologies may fit differently based on different factors, such as economics, environmental impacts, safety hazards, and public acceptability. How well different technologies match up against different applications will inform how much of an impact the new technologies (e.g., hydrogen fuel cells) could make on the given application. Therefore, it may be useful to consider a "score" for how well a given technology matches a given application: an impact figure of merit.

An impact figure of merit is a score from 0.0 to 10.0 in which higher scores are better (i.e., 10.0 is the best score). Importantly, not only economics should be considered when thinking about a new technology, but it may also be useful to think about five different categories: economics, environmental, safety, performance, and public acceptability. Each of these categories can be thought of to have its own impact figure of merit. Going one step further, individual topics or considerations within each category could also be thought of to have their own impact figures of merit. For example, individual topics within the Environmental category could be different types of emissions or the possibility of an environmentally damaging fuel spill. At each level (i.e., topic to category, category to overall) the individual impact figures of merit could be combined into a single impact figure of merit. This can be done using a simple average or by weighting certain topics or categories as more important than the others. The total overall score indicates the technology option and railway application pairing that best addresses the overall set of objectives.

This impact figure of merit framework provides a way to compare different types of very disparate information. However, it should be emphasized that for the purposes of this discussion, specific numbers will not be used; the research team discusses the approach at a high level here. This impact figure of merit framework provides a way to organize the assessment and could be used for more detailed assessments, but this report will remain at a high level to highlight tradeoffs for different technologies and applications. Appendix A gives an example calculation, which describes in more detail how the impact figure of merit can be calculated for environmental considerations.

2.1 Environmental Figure of Merit

The first category to consider is environmental impacts. An important metric to consider is the pollutant emissions per hour of operation, such as carbon dioxide, nitrogen oxide compounds (NO_x), hydrocarbons (HC), and particulate matter (PM). The amount of pollution generated per hour varies based on the amount of idle time, acceleration and deceleration, and constant velocity travel. Because of this, rail applications that involve significant amounts of idling and stop and go movement, such as switcher locomotives, generate more pollution than more constant-velocity long haul freight locomotives. A specific duty cycle can be assumed for each of the three applications (i.e., freight, passenger, and switcher) which would give information about how much time the locomotive would spend operating in a particular "notch," which is a description of eight different levels of power output. By then assuming a rate of fuel consumption (i.e., engine efficiency) for the different power output notches, the fuel consumption can be calculated over the course of the duty cycle. Finally, current U.S. Environmental Protection Agency (EPA) Tier 4 emission standards can be used to calculate the emissions for the diesel fuel consumed based on the duty cycle.

Another important environmental consideration is fuel spills; diesel fuel, like other hydrocarbon fuels, can negatively affect the ground on which the fuel is spilled and leads to soil or groundwater contamination. By contrast, battery electric trains will not have a significant environment impact due to a "spill" of batteries; there could be electrolyte, but it is in relatively small quantities. Some battery components like heavy metals are indeed hazardous (i.e., making them an environmental disposal hazard) but are in relatively smaller quantities and less likely to flow into topsoil and groundwater from a rail accident. Different battery technologies (e.g., lithium-ion) will have different environmental hazards depending on the composition of the battery. Hydrogen gas leaks are typically buoyant and will not affect topsoil or groundwater. The release of hydrogen into the atmosphere is not an environmental issue since hydrogen is non-toxic and not a greenhouse gas.

2.2 Acceptance Figure of Merit

Another important consideration for a new technology is public acceptance. This can include noise, aesthetics, and perceptions of the fuel itself. For light-duty vehicles, hydrogen fuel cell and battery electric vehicles are nearly silent compared to internal combustion engine vehicles. This could lead to greater public acceptance of the non-diesel locomotive technologies. However, most of the sound from a train is mostly wheel noise due to the metal-metal contact between the wheels and the track during normal operation and when applying the brakes. This is especially true for rail cars located away from the locomotive itself. This means that the public would likely not notice a large difference in noise levels based on the locomotive technology. Additionally, train signals like horn blowing are required regardless of locomotive technology.

Aesthetics are also important for public acceptance. Local smog production and smell would be higher for diesel-powered locomotives, and so might lead to a lower level of acceptance from the public. For electrified track, catenary lines are seen as unsightly and so would be viewed negatively by the public. Any kind of third-rail installation would need significant fencing to protect the public, which could also be unsightly. Battery and fuel cell electric trains would both be beneficial from these aesthetic standpoints, since they would not produce smog, smell, or have visible infrastructure along the track.

Finally, hydrogen itself may be viewed negatively by the public due to a perceived increased level of risk. Safety considerations themselves are considered in a separate category, but the public perception may reduce the willingness to support local changes in the short-term. This can be addressed by increased education and experience with hydrogen as a fuel.

2.3 Safety Figure of Merit

Safety considerations per fuel source and technology vary based on potential effects of a fuel leak and the health hazards posed during regular operations. All the fuels being considered (e.g., diesel, hydrogen, batteries) can result in a fire, either through defects (e.g., batteries) or via unintentional release and ignition of the fuel (e.g., diesel, hydrogen). Arguably, electrified track is unable to directly cause a fire from the release of electricity, but exposed electrified lines could ignite other combustible materials. Hydrogen fires can occur much more quickly and could reach relatively higher flame temperatures. However, hydrogen fires do not produce soot and thus radiate less heat as a result of a fire. Hydrogen fires can be nearly invisible in daylight, making them harder to detect. Additionally, hydrogen stored under pressure could result in a leak/flame that reaches further away from the source of leak, relative to diesel or batteries. Diesel and battery fires can last for much longer times, increasing the hazard due to more exposure time. Batteries contain two fire hazards: combustible materials (plastics) and flammable off-gas mixture which could include hydrogen, carbon monoxide, methane, and other gases.

Another type of hazard is health hazards, specifically for acute health hazards due to diesel emissions. This can decrease local air quality due to soot and other emissions from the diesel combustion. Arguably, diesel exhaust contains longer-term, chronic effects of health hazards, such as increased cancer risk. Such chronic health impacts may also occur due to hazardous materials release from a damaged battery. Hydrogen does not present any known chronic health effects. Exposure to LH_2 or cold hydrogen vapors can cause frostbite and should be avoided.

Another hazard is exposure to electricity. All the current technologies being considered use electricity, including diesel-electric locomotives, and so high-voltage electricity is present on-board the locomotive. However, for electrified track (i.e., third-rail or catenary lines) there is also opportunity for exposure of the public to additional high-voltage lines external to the locomotive. There are typically significant protections such as fencing to keep the public away from electric high-voltage lines, but the possibility of exposure remains. There would be no significant exposure to high-voltage lines outside of the locomotive for the other technologies.

Finally, high-pressure (HP) gas is a separate hazard that should be considered. This would only apply to the HP gaseous storage of hydrogen; even aside from the fire hazard of spontaneous ignition of a HP hydrogen release, the sudden release of HP gas could cause a significant physical hazard. This may be caused by a rapid blowdown of a leak or tank failure, which could lead to high-momentum gas (i.e., shock wave) resulting in physical harm or dangerous projectiles. This highlights the need for proper pressure relief to be incorporated into the systems on-board the locomotive, and to prevent physical damage to the HP vessels as much as possible. Additional research in the crash testing of hydrogen fueled locomotives and tenders to mitigate risk in this area is advised.

2.4 Performance Figure of Merit

Another category of considerations is how well a given technology matches the operational needs of a given application. These considerations are related to the economics, but they are considered here so as to be more explicit and directly discussed. The first consideration in this category is the weight and volume of the fuel on-board the locomotive. Compared to diesel fuel, hydrogen has a higher energy density per unit mass, but a lower energy density per unit volume. Generally, it could be assumed that lowering the fuel weight in transportation would be beneficial, as this would allow more of the motive power to moving the actual cargo or passenger weight. However, in the case of locomotives in particular, the research team modified this assumption because locomotives need a minimum amount of weight to achieve traction on the rails. Thus, additional weight on the locomotive is beneficial to provide additional traction. By contrast, if the hydrogen or other fuel were located in a tender car rather than the locomotive itself (e.g., LH_2), the lighter weight in this case would be beneficial; tender car weight only provides drag on the locomotive and does not provide additional traction. Depending on the rail application, the fuel (e.g., diesel, hydrogen, or battery) mass and volume may not enable a sufficient locomotive range between refueling, but this would need to be considered on more of a case-by-case basis. Of course, the weight and mass of fuel on-board the locomotive would not apply to an electric locomotive that relies on electrified track, since the "fuel" (electricity) exists in the third rail or catenary line, not stored on-board the train.

Another consideration related to the weight and volume of stored fuel is the fuel or energy efficiency of the locomotive. This can vary significantly based on different types of fuel, but generally a fuel cell or a battery would be more efficient than a combustion engine. Furthermore, diesel engines have reduced efficiency in lower notches (i.e., lower power output). This varies based on application because for long-haul freight, the locomotive might spend significantly more time in the higher more efficient notches, whereas a local passenger or switcher locomotive might spend significantly more time in the lower less efficient notches. Individual fuel cells also have reduced efficiency in lower fractions of the rated maximum power output; that said, fuel cell systems could operate in more of a modular configuration. Specifically, at lower system power outputs, instead of operating multiple fuel cells at low power, some fuel cells could simply be turned off and others operated at higher rated power, giving a much higher effective efficiency on a system-level.

Another important consideration is the maintenance interval and system life of a given technology. As a new technology for rail, this information is not available, and so this is a difficult direct comparison to make at this time. However, it is worth pointing out that a fuel cell or battery electric system would have significantly fewer moving parts than a diesel combustion engine, and so may lead to fewer maintenance needs in the long-term. Of course, this is not to say that fuel cell and battery electric systems would not need maintenance; fuel cells can become poisoned and batteries need to be replaced. It is worth noting that a transition to any new fuel type will require changes to operating procedures as well as retooling and retraining of maintenance facilities and personnel. This may be disruptive to the performance of a new technology in the short-term but would improve over the longer term.

A final consideration for performance has to do with refueling time. Any locomotive generally cannot be in service while refueling. One possible exception is a passenger train that could recharge on-board batteries while passengers are loading and unloading. However, especially for local passenger trains with multiple stops, this would likely not be longer than a few minutes, which may not be enough time for any significant battery recharging. As for the other fuel technologies that need to refuel or recharge, the specifics of refueling time will depend greatly on locomotive design and expected loading and distance. There are many ways in which refueling can be accomplished quickly, and so it is difficult to say that one type of fuel will always be faster or slower than another. That said, it is worth noting that current light-duty vehicle technologies for battery electric vehicles take upwards of an hour for a full charge (i.e., this can vary based on charging voltage, battery management system, and battery design), while fuel cell electric vehicles refuel in 5 minutes or less due to the ease of refueling with high-pressure hydrogen gas. Battery packs or fuel tanks could be exchanged rather than refueling or recharging on-board; however, this is likely to incur significant additional capital cost for extra tanks and batteries. Thus, for applications in which an extended refueling time would be a significant cost or delay in service, fuels cells may be especially beneficial.

2.5 Economic Figure of Merit

Finally, economic considerations are critical for deciding which technology will be adopted. Diesel locomotives are the current baseline technology for rail, and so the costs will be considered as relative to those costs. The first category of economic costs are capital costs: the cost of the new or modified locomotive, the cost of a new tender car (if needed), track or infrastructure modifications, and refueling and maintenance facilities comprise the direct costs. The cost of a hydrogen fuel cell or battery electric locomotive is difficult to predict; the first locomotives developed would almost certainly be more expensive than existing locomotives, as a new technology. However, as the technology and designs improve and mature, and the technology is made in greater numbers, the cost will come down. Even current commercially available fuel cell systems may not be rated for rail service, and modifications to these components may or may not introduce additional costs. Capital costs would also include the cost of electrification of the track via third rail or catenary lines (if used), whereas diesel, fuel cell, and battery electric locomotives will be able to use existing track.

Operating costs are also important to consider. The cost of the fuel itself is the most noteworthy: the cost of the diesel fuel used, the cost of the hydrogen fuel used, the cost of the electricity used for electric track or battery electric. Of course, with non-diesel electric technologies, the fuel (i.e., hydrogen or electricity) can be produced off-site and delivered or generated on-site; either way, the costs need to be considered, either by considering capital cost of the on-site production or by considering the purchased cost of the fuel itself. Additionally, maintenance costs should be considered; as discussed in the Performance Figure of Merit section, non-diesel technologies may require less maintenance than diesel. The labor hours of refueling and maintenance will contribute directly to the operating costs throughout the lifetime of the locomotive.

Finally, it may be useful to consider a third category of costs related to transitioning to a new fuel. These "transition" costs would generally fall into the capital and operating costs described above but are introduced due to the transition to a new fuel, rather than the use of existing infrastructure. If a new diesel locomotive is to be purchased and used, it can generally rely on existing refueling and maintenance facilities, rather than calculating the cost of building up new facilities from scratch. By contrast, if a non-diesel locomotive were to be purchased, even if the locomotive itself costs exactly the same, the costs of transitioning to this new fuel is likely to impose additional costs as well. The most obvious of these costs are the need for new refueling and maintenance facilities and infrastructure. If only a single route or locomotive uses the new fuel, then the rail network becomes fragmented; the new locomotive can only refuel at specific locations, maintenance staff trained on one type of fuel may not be able to work on the other type of fuel, and these can cause scheduling disruptions and operational issues. This is true with any type of fuel adoption and transition and must be considered for any potential projects. Isolated, shorter distance projects may be able to minimize these costs because the only facilities needed are the ones directly involved with the project, but even then, the new locomotive might not be as easily used for other tasks. These are not insurmountable obstacles but must be considered for a full analysis.

2.6 Impact Figure of Merit Summary

The impact figure of merit approach allows a numerical score to be assigned to the impact or quality of a technology in such areas as environmental, acceptance, safety, performance, and economics. The methodology allows for accounting of technology performance and benefits, while bringing those analyses together in a broad rating of one technology compared to another. The research team believe this approach will have utility in examining alternative rail technology options.

3. Assessment of Rail Standards for Hydrogen Applicability

The research team conducted an assessment of requirements between several AAR MSRP standards to determine gaps for hydrogen technology for rail applications. The research team reviewed the MSRP Section T (M-1004) (Association of American Railroads Section T, 2019), Section C Part III (M-1002) (Association of American Railroads Section C-III, 2014), and Section M (Association of American Railroads Section M, 2008) standards to determine potential issues or gaps with applying these requirements to hydrogen propulsion systems. Additionally, related requirements in hydrogen-specific safety standards were included as much as possible for each gap identified. These were from the National Fire Protection Association (NFPA) 2 Hydrogen Technologies Code (National Fire Protection Association 2, 2020) and American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA) G-095A Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A, 2017) documents. The intention is that these hydrogen-specific standards could help inform potential ways to address some of these gaps by giving example requirements from other industries.

3.1 Hydrogen Applicability Gaps for AAR MSRP Section T

Overall, the strategy for safe implementation set forth in M-1004 should be applicable for establishing a fuel tender based on the use of compressed hydrogen or LH_2, with some revisions of the requirements related to the physical differences between hydrogen and natural gas. The research team identified specific gaps in this section, along with potential ways in which these gaps could be addressed.

3.1.1 M-1004 Section 2.4.2: Materials for Inner Tank

The M-1004 specification emphasizes the inner material for natural gas fuel tank because of its high importance to the operation, longevity, and maintenance of fuel tanks. The requirement is specifically stated in Section 2.4.2: Materials for Inner Tank: *"Stainless steel of ASTM A240A, Type 304 or 304L shall be used for the inner tank…"* For hydrogen tanks, there are several industry-accepted choices for the material of the inner tank. For high-pressure hydrogen tanks, the inner liner can be aluminum (Type III tanks) or a polymer (Type IV) tanks. For a LH_2 tank, the inner liner can be either 316 stainless steel (316 or 316L) or 304 stainless steel (either 304 or 304L). While 304 stainless steel is not recommended for room temperature hydrogen exposure (due to embrittlement concerns), it is allowed for cryogenic temperatures where hydrogen embrittlement is limited due to slow diffusion.

Section 6.1.3 of ANSI/AIAA G-095A lists materials for cryogenic use for LH_2, specifically 3.5-nickel (Ni) steel, 5-Ni steel, and 9-Ni steel. Tables 19 and 20 of ANSI/AIAA G-095A address material selection for various components; Table 20 specifically lists 304, 304L, 316, or 316L stainless steels for LH_2 dewars. Section A.8.3.1.2.3 of NFPA 2 discusses in general terms which type of alloys are acceptable for liquefied hydrogen such as; chromium-Ni alloys, certain copper alloys, and aluminum. If gaseous hydrogen (GH_2) is used, Section A.10.3.6.3 of NFPA 2 lists materials that should not be used; grey/ductile/cast iron, certain stainless steels, Ni, Inconel, Monel, 2.25-Ni, 3.5-Ni, 9-Ni.

3.1.2 M-1004 Section 2.4.2.2: Impact Testing Temperature

The M-1004 specification emphasizes the impact testing of fuel tanks at the operational temperature because rail accidents will involve high shock/vibration impacts at the tank operational temperature. Section 2.4.2.2 specifically states: *"For approved M-1002 materials other than Type 304 or 304L, impact tests shall be conducted at …the tank design service temperature of -320 °F (77 K)."* There is a technical gap between this specification and tanks needed for LH_2 because the operational temperature of a LH_2 tank is 21 K (-421.87 °F). To keep with the intent of the specification, tank impact testing would need to be conducted at 21 K. However, there is a need for further research and development to determine if an assessment of impact tests can take place at a higher temperature such as 77 K (-321.07 °F) to sufficiently capture the mechanical effects that would occur at 21 K. Testing at 77 K is more desirable because at 77 K liquid nitrogen (LN_2) can be used; LN_2 is non-flammable and less expensive than LH_2 or liquid helium which would be needed for testing at 21 K.

Neither NFPA 2 nor ANSI/AIAA G-095A address testing specifications for LH_2 tanks; stationary systems use both standards. NFPA 2 section 8.1.2 does state that the design, construction, maintenance, and testing of LH_2 containers be done and maintained in accordance with U.S. DOT regulations, Transport Canada (TC), Transportation of Dangerous Goods Regulations, American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), or other administering agencies. Section 7.3.7 of ANSI/AIAA G-095A states that cryogenic components and systems shall be tested prior to acceptance for operation use, and vessels be tested in accordance with ASME BPVC.

3.1.3 M-1004 Section 2.4.5: Thickness of Inner Tank Shell

The M-1004 specification incorporates requirements on the inner tank shell thickness because it increases durability in operation, and survivability in a crash environment. Section 2.4.5: Thickness of Inner Tank Shell states the following requirement: *"The minimum wall thickness after forming of the inner tanks shell must be 0.5 in or that calculated by the following formula…."* A technical gap exists between this specification and the current industrial practice for HP hydrogen tanks and LH_2 tanks. For HP Type III tanks, the inner aluminum liner thickness is chosen for manufacturability and to provide a baseline pressure rating. For example, for a 5,000 psi (350 bar) hydrogen tank, the aluminum liner provides by itself a pressure rating of ~3,500 psi (240 bar) and the thickness of the composite overwrap is chosen to improve the pressure rating of the tank. For Type IV tanks with a polymer inner lining, the inner liner thickness is chosen to provides a good diffusion barrier to hydrogen with the over-wrap providing almost all the tank pressure capability. This HP tank architecture of an inner liner with an over-wrap needs to be technically accommodated in a revised M-1004 that addresses gaseous hydrogen technology.

For large LH_2 tank designs (4,000 kg) used on LH_2 transport trailers, the inner liner is ~0.375-in thick 304 or 316 stainless steel (i.e., chosen for inner shell stability), with an outer carbon steel thickness of 0.25 in. LH_2 is a very light fuel, much lighter than LNG, meaning that thinner tank walls can be used. The molecular mass of hydrogen (H_2) is 2 grams/mole whereas that of methane (CH_4) is 16 grams/mole. Thinner tank walls can have significant benefits with respect to heat transfer, both in terms of reducing the thermal mass of the tank wall itself and by providing a shorter distance to the vacuum-insulated annular space. Again, a revised M-1004 specification that includes LH_2 tank technology would need to consider the inner and outer shell architecture that current non-rail specific LH_2 tanks possess.

Section 8.3.2.1.5.1 of NFPA 2 requires that the inner vessel of LH_2 storage tanks be designed and constructed in accordance with the ASME BPVC and be vacuum jacketed. NFPA 2 does not directly specify a specific minimum thickness required for the inner tank shell, but does specify for compressed GH_2 containers should not be used if after examination if they have "flaws or inclusions exceeding the lesser of 5 percent of the wall thickness or 0.12 in. (3 mm)" in Section 7.3.2.4.1.2. ANSI/AIAA G-095A does not specifically address minimum wall thickness for LH_2 tanks, but Section 8.2.2 states that the inner vessel should be designed to have a vapor-tight seal, and Table B2 in Section B.6.3 does reference that inner tanks for GH_2 and LH_2 need to meet the individual specification requirements in 49 CFR § 179.401.

3.1.4 M-1004 Section 2.4.8: Jacket Design

The M-1004 specification incorporates requirements on the jacket (i.e., the outermost shell of an LNG tank) design because it can be an indicator of durability in operation, and survivability in a crash environment. Section 2.4.8: Jacket Design states: *"The minimum wall thickness, after forming of the jacket shell and heads shall not be less than 0.5625 in."* There is a technical gap between this specification and LH_2 tank technology. As indicated above, for LH_2 tanks with 4,000 kg capacity, the outer shell thickness is typically 0.25 inches. There may be less of a technical gap here for the outer jacket of the cryogenic tank; there are benefits to heat transfer for having a thinner inner tank wall, but less so for the outer jacket. As such, this requirement should be analyzed further, but this may not be a significant technical gap.

3.1.5 M-1004 Section 2.4.15: Access to Inner Tank

The M-1004 specification emphasizes the need for physical access into the interior of fuel tanks, without stating why this access is needed. Section 2.4.15: Access to Inner Tank specifically states: *"The inner tank shall be provided with a means of access having a minimum inside diameter of 16 inches."* There is a very important gap between this specification and the design of LH_2 tanks. The research team is unaware of a maintenance reason as to a requirement for access once the tank is installed and in-use, and discussions with cryogenic tank manufacturers indicated that this is not required. Access may be required for instrumentation (e.g., in aeronautic applications) but this is likely not needed for storage and rail applications. Access could be required for inspection, but this could be problematic for cryogenic tanks. Conversations with tank manufactures and AAR experts indicated that if physical access was needed to the inside of a cryogenic tank, an opening would simply be created manually (e.g., cut or grinded) and repaired afterwards; a removeable access door or hatch would not be used. Any time a cryogenic tank is opened to the air, significant icing may occur, and the tank would need to be fully evacuated of air before service; this would be a major impediment to usage after access in this manner. The need for such access should be reviewed in the context of LH_2 storage for rail applications.

Neither NFPA 2 nor ANSI/AIAA G-095A has a similar requirement for access to the inner tank. Of course, if access is indeed required, then additional considerations may apply for confined space access and flammable gas concentration limits within the tank before access.

3.1.6 M-1004 Section 5.4.7: Pipe Jacketing for LNG Tenders

The management of pipe jacketing, particularly where the pipes enter the LNG tank proper, is critical for safe operation of the system because they are a potential source of flammable vapor leak. It is also important to keep these pipes from encountering impacts. Section 5.4.7: Pipe Jacketing for LNG Tenders specifically discusses this in the following: *"All cryogenic liquid piping that is external to a protective housing, accessible from ground level, and/or adjacent to safety appliances shall be protected from incidental contact, e.g., jacketing or guarding."* This requirement would seem to apply to hydrogen systems as well but brings up an important point that is worth discussing. In maritime applications, a tank connection space (TCS) is an actively ventilated box with a hydrogen detector inside, appended to the LH_2 tank where all the piping and valving out of the tank is housed. Such a construct is also used for LNG tanks on ships.

Neither NFPA 2 nor ANSI/AIAA G-095A specify a tank connection space directly. Both standards do have requirements regarding jacketing of cryogenic pipes. Section 8.3.2.1.5.1 of NFPA 2 addresses that the inner vessel of LH_2 storage tanks shall be designed and constructed in accordance with ASME BPVC and shall be vacuum jacketed. Section 8.3.2.1.5.2 addresses construction of the vacuum jacket directly, that it shall be designed to withstand the maximum internal and external pressure that it will be subjected to even at emergency pressure relief of the annular space between the inner and outer vessel. The jacket shall be designed to withstand a minimum collapsing pressure differential of 30 psi, vacuum level pressure shall be monitored within the annular space, and the connection shall be fitted with bellows-sealed to protect against damage from impact. Similar requirements apply for underground tanks laid out in section 8.3.2.3.1.7. Section 8.2.2 of ANSI/AIAA G-095A addresses that inner vessel should be designed to have a vapor-tight seal in the outer jacket to prevent air condensation. Section 8.3.4 addresses that expansion joints are usually placed in the outer jacket and that the inner pipe usually is supported within the vacuum jacket by spacers in the annulus. Section 8.5.5 states that the jacket system should be protected with a relief valve that should limit the pressure in the annulus to not more than 10 percent above the lesser of the external design pressure of the inner line or the design pressure of the jacket.

3.1.7 M-1004 Section 5.7.1: Pressure-relief Devices (PRD) General

Pressure-relief devices (PRD) are one of the most important safety devices for the use of compressed gases for fuel, such as compressed natural gas (CNG), or for cryogenic fuels that can become pressurized by loss of thermal insulation or fire. This is specifically mentioned in Section 5.7.1: Pressure-relief Devices (PRD) General, subsection 5.7.1.1.3: *"The primary device must be sized to handle loss of vacuum and the secondary device must be sized to handle loss of vacuum with tender in a pool fire."* There are technical gaps between this specification and the existing hydrogen practice. First, PRDs are also used to provide pressure safety for gaseous hydrogen systems; there is no vacuum as part of gaseous hydrogen storage, as hydrogen is typically stored at ambient temperature but high pressure. Therefore, requirements would need to be written specifically for GH_2 tank PRDs. For LH_2 tanks, the PRDs are usually arranged to have two duplicate PRDs on the inner tank space that can be toggled together. This allows a PRD to be taken offline to receive maintenance (or in case one freezes over) without loss of overpressure protection on the inner tanks space. There is a third overpressure protection on the inner tank, a rupture disk sized to allow full tank venting in the event of a fire. The outer LH_2 tank also has a

PRD and rupture disc to allow for hydrogen venting if there is a hydrogen leak into the interspace annular region between the inner and outer shells.

Neither NFPA 2 or ANSI/AIAA G-095A address a loss of vacuum or a pool fire. Sections 7.1.5.5 and 8.1.4.1.1 of NFPA addresses PRDs for GH_2 and LH_2 systems, respectively, stating that they shall be provided to protect containers and systems from ruptures. PRDs shall be designed in accordance with CGA S-1.1, CGA S-1.2, and CGA S-1.3. Section 7.1.16 addresses GH_2 venting systems which vent to the atmosphere in accordance with CGA S-5.5. Section 8.1.4.7.2.2 addresses the use of multiple PRDs, each valve installed provides the required flow through the relief devices at all times. Sections 10.3.2 and 11.3.1.5 address PRDs for GH_2 and LH_2 vehicle fueling facilities, respectively, and have similar requirements as outlined above. Section 5.1.1 of ANSI/AIAA G-095A states that cryogenic hydrogen requires the use of pressure relief valves to avoid over-pressurization, container rupture, and explosion hazards. Section 8.2.2 requires PRDs for inner vessels and vacuum jackets of LH_2 systems and shall be set in accordance with ASME BPVC. The inner vessel relief device shall be sized in accordance with CGA Pamphlet S-1, API RP-50, and RP-521 Section 8.5. Parallel redundant relief decides are recommended for inner LH_2 vessels to mitigate concerns of inoperability due to frozen inlets. Section 8.5.4 states that supplemental PRDs should be installed to protect against excessive pressures due to fire exposure or other external heat sources.

3.1.8 M-1004 Section 5.8.10: Leak Detection

Section 5.8.10: Leak Detection states: *"The leak detection shall be set to alarm at 20% LEL and shut down the tender at 50% LEL."* There is a very important gap between this specification and the safe use of hydrogen fuel cell technology. In the case of H_2, the leak detection emphasis should be on fires, not just explosions; fires are dangerous too, and if fires are being prevented, so are explosions. This could be due to the terms for the lower flammability limit (LFL) and not the lower explosion limit (LEL) being used interchangeably in many documents, such as sensor documentation, safety analyses, and technical reports. There is not always a clear definition of "explosion" and so different sources can report different upper and lower limits of concentration. A flame can produce a thermal hazard without any explosion, and this should also be protected against in the safety requirement. The definition of LEL in the M-1004 document specifically notes the ability to produce a flash fire, which may not match an intuitive understanding of explosions to the layperson. Therefore, the research team would argue that the standards should reference the LFL rather than the LEL, but it is understandable that the LEL is widely used by many in the fire safety community and may be used interchangeably with the LFL. Regardless, the flammability or explosion limits within the standard should be defined explicitly in the document to remove any ambiguity. For hydrogen, the LFL is 4 percent by volume fuel/air mix and for methane (a main constituent in natural gas) the LFL is 5 percent by volume in air. Defining these values explicitly in the document would remove any ambiguity between LFL and LEL and make it explicit as to what concentration level the alarm and shutdown should occur.

NFPA lists many requirements for storage, production, and other systems that activate emergency shutdown systems, start or increase mechanical ventilation, alarm activation, and shut off the hydrogen source once detection of 25 percent of the LFL is reached. For example, NFPA 2 Section 7.1.22.14.2.2 requires the activation of the emergency shutdown system upon detection of 25 percent of LFL. Similarly, Section 9.1.2 of ANSI/AIAA G-095A gives requirements for maximum allowable concentrations of 25 percent of LFL, as well as alarm activation, system shutoff, and ventilation at 25 percent of LFL. For both NFPA 2 and ANSI/AIAA G-095A, sensitive or critical systems are recommended to have alarms, ventilation, and shutdowns occur at 10 percent of LFL. For example, NFPA 2 Section 13.3.1.2.3 requires ventilation activation at 10 percent of LFL (i.e., if constant ventilation is not used) and Section 7.4.5 in ANSI/AIAA G-095A gives a limit of 10 percent of LFL for permit-required confined spaces.

3.1.9 M-1004 Section 5.10.1: Heat Exchanger

Systems using cryogenic fuels typically need the fuel to be warmed up prior to use in the energy conversion device (e.g., engine, fuel cell, etc.). The specific requirement is given in Section 5.10.1: Heat Exchanger (HEX). *"Two heat exchangers are required per tender, and each heat exchanger must be sized and designed to independently supply the fuel demand…"* There may exist a technical gap in the regulations in comparison to the hydrogen industry regarding the need for a duplicate heat exchanger. The two heat exchangers for LNG tenders in M-1004 are not redundant, but rather meant to independently supply two different locomotives on either side of the tender car in the consist. Depending on how a hydrogen tender may be designed, there may only be a single heat exchanger needed to supply a single locomotive. While both NFPA 2 and ANSI/AIAA G-095A mention the need and use for heat exchangers, neither standard specifics the number of heat exchangers needed per tender.

3.1.10 M-1004 Section 5.12.3.6: LNG Return

Section 5.12.3.6: LNG Return states: *"The return piping is for instances when a locomotive(s) drops fuel demand and needs to return unused fuel to the bottom of the inner tank."* There is a technical gap between this specification and the nature of hydrogen fuel cells. This requirement does not exist with fuel-cell propulsion because the fueling system is "on demand," drawing hydrogen as it is needed from the fueling manifold. There is no return of hydrogen fuel to the hydrogen tank when hydrogen demand drops, the fuel is simply not taken from the fuel storage to begin with. Hydrogen flows from the storage through a gas regulator and when there is no draw on one side of the regulator, there is no flow. There is no need to keep the fuel cell operating with no demand, like there is for an engine.

3.1.11 M-1004 Section 5.14: Protective Housing for Tank Car-style Tenders

The M-1004 specification takes on the issue of air flow in the protective housing for fuel tenders because a fuel leak only becomes hazardous if the fuel/air mixture is in the flammable range between the LFL and upper flammable limit (UFL). Thus, air flow is a key strategy to mitigate the creation of a flammable air/fuel mix upon fuel leaking. The specific requirement is given in Section 5.14: Protective Housing for Tank Car-style Tenders: subsection 5.14.5. *"The protective housing design shall be a water-tight and vented (to prevent accumulation of vapor) enclosure…"* There exists a possible technical gap with the current technical use of hydrogen, because the use of the word "vented" is ambiguous. A space can be vented to allow the flow of gases or possibly explosion vented to safely redirect overpressures, but mechanical ventilation is a different topic. A passively ventilated system is possible, but not preferred as to more quickly dilute and dissipate hazardous conditions. The term "vented" should be defined more clearly in the document, and minimum active ventilation requirements should be explicitly specified where needed.

Neither the NFPA 2 nor ANSI/AIAA G-095A standards address venting of vehicle bodies, they do address indoor ventilation, gas cabinets, and exhausted enclosures. Section 6.18 of NFPA 2 addresses ventilation for indoor storage for both GH_2 and LH_2. The various subsections address the mechanical or fixed natural ventilation, design requirements, operational criteria, shutoff criteria, and exhaust criteria. Sections 6.19 and 6.20 address ventilation requirements for Gas Cabinets and Exhausted Enclosures, respectively. Section 7.4.5 of ANSI/AIAA G-095A addresses ventilation for any structure containing hydrogen system components.

3.1.12 M-1004 Section 8.1: Scope

Tender refueling is specifically addressed because it is in the fueling of a tender where there is increased risk of a fuel leak or accidental overfilling of a fuel tank. The specific requirement is given in Section 8.1: Scope: *"This chapter defines the interface between the tender and a tender-fill station supplying an alternate fuel."* There is a minor technical gap here, as it needs to be specified that the "tender fill station" could very well be a LH_2 delivery trailer. Alternatively, the filling station could be a fixed facility for transferring hydrogen to the tender. These two routes of hydrogen delivery may have different safety concerns. For example, there are recurring electrical grounding concerns and fueling line breakaway issues for mobile trailer refueling. These problems are resolved on installation for fixed refueling installations. Thus, the language should likely be modified to break out the trailer refueling and fixed facility refueling separately.

NFPA 2 Section 10.9 addresses outdoor nonpublic refueling from transport vehicles for GH_2, while Sections 10.1–10.7 give more general requirements for fixed refueling facilities. The section states that onsite storage shall be subject to the same requirements as permanent refueling storage installation with exception of vessel requirements. There are analogous separate sections in Chapter 11 of NFPA 2 for LH_2 refueling. Section 10.2.3 of ANSI/AIAA G-095A addresses the procedures for LH_2 filling trailers and storage vessels must be controlled to prevent overloading. Section B.4.1.1 addresses bulk storage vessels from point of fill connection to the point which hydrogen enters the distribution piping. Section B.4.1.2 addresses the requirements for the installation of GH_2 systems on consumer premises.

3.1.13 M-1004 Section 8.5.2: LNG Filling Interface Operating Parameters

The M-1004 specification calls out the temperature range applicable for the LNG fueling interface in Section 8.5.2: Table 8.1 LNG filling interface operating parameters. A technical gap exists between the lower temperature indicated in Table 8.1 and LH_2 operation. That lower temperature should be 21 K, or -421.9 °F, for LH_2 operation.

Section 10.5.1.3 of NFPA 2 addresses fueling protocols for Light-Duty Hydrogen motor vehicles, but the operating parameters for filling non-light-duty hydrogen do not yet exist. Section 11.3.4.7 of NFPA 2 addresses refueling from vehicle to mounted tank at commercial and industrial facilities. This section does not address the specific operating parameters for filling. Section 10.2.3 of ANSI/AIAA G-095A addresses loading operations for storage and transport vessels.

3.1.14 M-1004 Section 9.5.6: Venting of Car Body

The M-1004 specification identifies significant fuel venting occurring within a carbody as requiring mitigation. The requirement is specifically called in Section 9.5.6: Venting of Car Body. *"The tender car body shall be designed so as to prevent accumulation of gas. In addition,* *the tender car body shall be designed with sufficient venting capacity that in the event the largest individual fuel tank in the tender ruptures, the tender car body shall survive without portions of the car body becoming detached."* There is a technical gap between this statement and what is required for safe storage/use of hydrogen from a tank car. This M-1004 specification provides no detail on how this ventilation is to be achieved, nor is there a recommendation for the required ACH for active ventilation. It is very important for hydrogen that the carbody design prevents the accumulation of gas. The tank car roof structure should have an open path to the outside air, a path that does not allow ingress of weather (e.g., rain, snow) or animals/insects but would allow the escape of hydrogen should a large release occur. There is a similar concern with ambiguity of the word vented and ventilated as outlined in M-1004 Section 5.14: Protective Housing for Tank Car-style Tenders. The level of active ventilation required further study.

3.1.15 M-1004 Section 11.7: Dynamic Design Considerations

The specification M-1004 requires input to models of dynamic design down to the operational temperature of LNG tanks (110 K, -262 °F). Section 11.7: Dynamic Design Considerations, subsection 11.7.1.1 states: *"For simulation purposes, AAR will make available material characterization data for the inner tank at -260 degrees F."* For LH_2 operation, the inner tank temperature will be 21 K, or -421.9 °F. Thus, materials characterization data will be needed for design simulation input at this temperature.

3.1.16 M-1004 Appendix G Section 2.4: Wire Conduit and Harnesses

M-1004 specification requires tender wiring to be protected from liquids. While the specification does not identify the liquid of concern (e.g., water) the concern could also be contact with liquid fuels. Appendix G Section 2.4: Wire Conduit and Harnesses states the requirement: *"Tender wiring shall be routed and protected in a conduit… conduit must be liquid-tight flexible metal or rigid type with appropriate liquid tight fittings."* There is a possible technical gap between this requirement and operation of hydrogen systems, and the gap is centered on the location of the tender wiring. For tender wiring on the outside of the tender car, there is no gap. However, if the tender wiring is located inside the tender car, then the conduit should be gas tight, not just liquid tight, and furthermore, the conduit should be electrically grounded.

Both NFPA 2 and ANSI/AIAA G-095A discuss electrical wiring in several sections, in both cases the standards point back to NFPA 70 (National Electric Code). For example, Section 7.3.2 of ANSI/AIAA G-095A discusses the requirements for electrical equipment and wiring used in or near hydrogen systems and points to NFPA 70.

3.1.17 M-1004 Appendix G Section 2.10: Grounding/Bonding

The M-1004 specification calls out that the fuel tender and truck must be electrically connected via a grounding cable. This important requirement is to eliminate the buildup of static electricity, which when discharged in the presence of fuel vapors (e.g., from a fuel leak) can cause a fire. Appendix G Section 2.10: Grounding/Bonding, subsection 2.10.2 states the requirement: *"The tender shall be grounded to each truck frame by means of a separate cable that shall be sized to safely ground under normal conditions."* This specification constitutes a technical gap in the sense that the adopted electrical ground for the train needs to be identified. Since the tracks are not grounded, the truck may not really be ground. For LH_2 tender refueling, the truck itself must then be separately grounded to the same ground as the LH_2 refueling trailer. This highlights a broader point that tenders should be grounded when fueling either by truck or at a station.

Section 18.3.2.7 of NFPA 2 specifically addresses that cylinders, containers, or tanks and piping systems used for defueling shall be bonded and grounded in accordance with NFPA 77; there are several other sections throughout NFPA 2 that address the requirements for grounding and bonding of electrical wiring and equipment which typically point to NFPA 70. Sections 7.3.5.2, 7.3.5.4, 8.3.1, and 10.2.3 of ANSI/AIAA G-095A address grounding and bonding.

3.1.18 M-1004 Appendix I Section 2.2: Nitrogen Purge Assembly

The M-1004 specification properly focuses on the purge procedures for LNG fuel tenders. The purpose of purging is to remove air from the fueling lines and fuel manifold to not have oxygen in the lines along with the fuel. This is stated in Appendix I Section 2.2: Nitrogen Purge Assembly. A description is given of how to use N_2 to purge LNG lines. This represents a technical gap for operation with LH_2. Nitrogen can be used to purge LNG tanks and fuel lines because N_2 will not liquefy at the 110 K (-261.67 °F) temperature of LNG. However, since the liquefaction temperature of N_2 is 77 K (-321.07 °F), it will liquefy and even freeze at the 21 K (-421.87 °F) operating temperature of LH_2 lines, clogging the lines and preventing proper purging. Thus, while N_2 can be used to purge GH_2 lines that are above 77 K, it cannot be used to purge LH_2 lines. For LH_2 line purging, while helium can be used, it is very expensive. Instead, hydrogen gas itself can be purge the lines. This must be done in a safe way, such as first displacing the oxygen with nitrogen at ambient temperatures, followed by ambient temperature hydrogen gas to displace the nitrogen.

NFPA 2 Section 15.3.1 mentions the process of purging throughout the standard, although it does not specify which gas needs to be used. NFPA 2 states that the purge gas needs to be inert but does not state what type of gas it should be. Section 5.4.2.3 of ANSI/AIAA G-095A mentions that N_2 is often used as a purge gas but does not require N_2 be used as the purge gas. Section F.10.2.1 of ANSI/AIAA G-095A does suggest the use of helium or GH_2 to purge instead of oxygen or N_2 due to the possibility of condensing or solidifying.

3.1.19 M-1004 Appendix J Section 4.4.7: Fuel Tanks

Leak detection is a very important feature for the safe operation of any lighter than air fuel such as natural gas or hydrogen. Appendix J Section 4.4.7: Fuel Tanks specifies this: *"Inspect the fuel tank for visible or audible leaks of LNG external to the fuel tank. The location of the leak will be evidenced by clear, colorless, smoking liquid combined with frost build-up of the area."* There is a technical gap in this regulation not only in its application to the use of LH_2 technology, but LNG as well. Listening for audible sounds and looking for smoking liquid (i.e., liquid that causes air condensation around it) is inadequate because, although it can detect very sizeable leaks, this approach can miss smaller leaks that can still be of concern. The industry standard for the external detection of hydrogen leaks is to use hand-held combustible gas detectors. This will certainly be needed for LH_2 tenders and should be used for the periodic inspection and leak checking of LNG tenders as well.

NFPA 2 has requirements for leak testing and detection throughout the standard, particularly for piping systems and dispensing systems, but does not address leak testing or detection directly for LH_2 tanks. Section 10.3.13 of NFPA 2 states that GH_2 dispensing equipment shall be provided hydrogen gas detection, leak detection, and flame detection at the fueling area. Section

8.1.3.1.9.1 of NFPA 2 states that LH_2 piping systems shall be tested and proved free of leaks after installation as required by the codes and standards to which they were designed and constructed. Section 7.11.2 of ANSI/AIAA G-095A states that a combination of portable and fixed hydrogen sensors should be used to detect hydrogen that meet Class I, Division I or II, Group B requirements of NFPA 70 as appropriate. Section 9.1 goes into some detail about considerations for detector locations and automatic shutdown based on detectors. Section 9.1.3 details several types of hydrogen detectors types.

3.1.20 Appendix J Section 5.2.7.2.4: Cryogenic Pump

The M-1004 specification addresses the operational status of cryogenic pumps used to move LNG from the LNG tank to the heat exchanger. Appendix J Section 5.2.7.2.4: Cryogenic Pump specifically states: *"If a tender is equipped with an internal cryogenic pump and the pump is not working, this is not considered a noncomplying condition and the tender may continue in service until it can be scheduled for pump maintenance."* For LNG or LH_2, a properly functioning cryogenic pump is important for the proper and safe operation of the fuel tender. Neither NFPA 2 nor ANSI/AIAA G-095A address the issue of operational status if the cryogenic pump fails.

3.1.21 Stratification and Rollover of LNG

There is no mention in M-1004 of "stratification" in the storage of LNG in insulated tanks, nor the possibility of "rollover" arising from the shifting of the stratified layers where there can be a sudden burst of pressure during refueling or other LNG mixing events. It is possible this was a simple omission and such a description for LNG would be a useful addition. Regardless, it has no impact for hydrogen refueling considerations, because there is no stratification in LH_2 tanks due to the uniform composition of the LH_2 load.

3.2 Hydrogen Applicability Gaps for AAR MSRP Section C Part III

The AAR MSRP M-1002 standard covers the design of tank cars for carrying cargo, not for fuel tenders. Overall, the strategy for safe implementation set forth in M-1002 should be applicable for a tank car carrying compressed hydrogen or LH_2, with some revisions of the requirements related to the physical differences between hydrogen and other materials. In particular, materials compatibility for hydrogen is important to consider in tank construction. Specific gaps identified in this document are identified here, along with potential ways in which these gaps could be addressed.

3.2.1 M-1002 Section 1.2: Definitions

Specification M-1002 does an excellent job defining terms in the beginning of the document. The research team recommends that two additional terms be defined: "eduction pipe" and "lading material."

3.2.2 M-1002 Section 1.4.6.1.2: Procedures for Approval of Pressure Relief Devices

Section 1.4.6.1.2 of the specification M-1002 properly discusses the need and importance of PRDs to provide safety for cryogenic fuel systems (i.e., where rapid warming of the cryogen in confined spaces can lead to high pressures) or for high pressure fuel storage systems. This is first stated in Section 1.4.6.1.2: Procedures for Approval of Pressure Relief Devices. However, M-

1002 indicates PRDs must be tested, but it is ambiguous at this point if testing all PRDs must occur, or just the PRD type (i.e., as indicated by one PRD out of many). This ambiguity needs to be resolved with the required testing clearly stated, and consistently discussed in the document. This is not hydrogen specific, but an important consideration for safety testing.

NFPA 2 Section 8.1.10.1.2 requires that PRDs shall be tested for operability and to determine if they are set at the relief pressure required by the tank design. Section 10.6.3 of NFPA 2 states that pressure relief valves protecting ASME pressure vessels shall be repaired, adjusted, and tested in accordance with applicable regulations. The valves shall be tested every 5 years in accordance with applicable design standard. Section 11.3.1.5.2 addresses the installation of PRDs on dispensing systems. Section 8.2.2 of ANSI/AIAA G-095A briefly mentions that PRDs shall be set in accordance with ASME BPVC. ANSI/AIAA G-095A does not directly address the testing requirements for PRDs prior to installation.

3.2.3 M-1002 Section 2.2.8: Electrical Bonding and Grounding

Electrical bonding and grounding are among the most important safety concerns for the safe use of hydrogen fuel cell technology in any environment. Section 2.2.8: Electrical Bonding and Grounding states: *"All tank cars must have two electrical grounding lugs accessible on opposite sides of the car…"* There is a minor technical gap in this specification with regard to hydrogen. Since the train tracks are not grounded, the true electrical ground of the locomotive and tank cars needs to be clearly identified. Both grounding lugs on opposite sides of the car must tie to this common train grounding point.

3.2.4 M-1002 Section 2.2.15.2: Thermal Protection Systems

A chief safety concern of hydrogen technology is to construct the system to safely release high pressure buildup within a vessel that might result from a fire. The issue of tank car response to fire is stated explicitly in M-1002 Section 2.2.15.2 Thermal Protection Systems: *"Each combination of tank car, pressure relief device, thermal protection system, and lading material must be capable of withstanding a full-immersion pool fire for 100 minutes and a torch fire for 30 minutes under the conditions described…"* There is a possible technical gap between this specification and hydrogen technology that arises from ambiguity. Specifically, whether the tank itself or the tank car enclosure which surrounds and protects the fuel tank is expected to satisfy these requirements. This language needs to be clarified, for both LH_2 tanks and high-pressure tanks that will be used in hydrogen rail technology. NFPA 2 or ANSI/AIAA G-095A does not address specific requirements for tank cars or systems to meet for pool or torch fires. Both standards do address mitigative systems to help prevent ruptures due to fires. Including detection and monitoring systems, PRDs, and fire protection systems as some examples.

3.2.5 M-1002 Section 3.2.3: Insulation

Cryogenic tanks (e.g., LNG and LH_2) will always have some boil-off because tank insulation is not perfect. The requirement on cryogenic tank insulation is stated in Section 3.2.3: Insulation: *"The insulation system must be such that the normal evaporate rate (NER) will be less than 0.75% per 24-hour day of the full liquid nitrogen payload…."* There is a technical gap between this specification and existing hydrogen technology. It is much more difficult to achieve low boil-off with LH_2 because it takes much less heat (6.6 times less energy) to evaporate LH_2 compared to LN_2. While large LH_2 tanks, holding 4,000 kg, can achieve the stated evaporation rate of 0.5%/day, smaller LH_2 tanks will have increasingly higher evaporation rates. As such, the practical ability to meet this evaporation rate will depend on the size of the LH_2 tank.

NFPA 2 does not address specific NER values but does discuss the need for insulation to prevent vapor loss. Section 8.3.1.2.3.8 states that the insulation on piping systems shall not be made of noncombustible material and be vapor tight to prevent condensation of air and oxygen enrichment. Section 5.4.2.3 of ANSI/AIAA G-095A addresses the concern of evaporation of condensation which could lead to further oxygen enrichment, which is an explosion hazard, but does not specify a specific evaporation rate from the tank.

3.2.6 M-1002 Section 3.2.5: Bursting Pressure

M-1002 Section 3.2.5: Bursting Pressure states: *"The minimum required bursting pressure of the inner container is 240 psi (1655 kPa)."* There is a possible technical gap between this specification and LH_2 storage of hydrogen. There is no gap for high-pressure hydrogen storage, which operate far above this minimum anyway. For LH_2, the burst pressure protection is usually set at a maximum of 150 psi, meaning the LH_2 tank pressure relief valve is set at 150 psi, which is significantly lower than the stated burst pressure of 240 psi in M-1002 as indicated. An LH_2 tank has both an inner and outer tank, and each requires its own pressure relief strategy that requires specification in a revised M-1002. The inner liner of a LH_2 tank will have redundant PRDs in sequentially higher pressure and rated flow rate to allow routine relief of boil-off gases (i.e., typically at 150 psi) and then at 175 psi to handle a higher-pressure incident, with the last pressure relief being a rupture disc set for ~200 psi, which allows a very high flow rate of gas for a major inner tank overpressure. In addition, the outer liner has typically its own rupture disc to allow for venting of the tank interspace in the event of a fire or major malfunction of the tank. Annex Section A.8.3.1.2.8.5 of NFPA 2 notes that maximum allowable working pressures (MAWP) range from 150 to 250 psig, with the majority being limited to 150 psig. Neither NFPA 2 nor ANSI/AIAA G-095A give specific relief or bursting pressures; rather, this depends on the design pressure of the tank itself.

3.2.7 M-1002 Section 3.4.18: Tests of Pressure Relief Valves

The importance of pressure relief device testing is stated in Section 3.4.18: Tests of Pressure Relief Valves: *"Each valve must be tested by air or gas for compliance with paragraph 3.4.23 (AAR.401) before being put into service."* This would seem to resolve the technical gap ambiguity concern indicated previously (Section 3.2.2) if this posture of testing all PRDs is maintained in the rest of the document.

3.2.8 M-1002 Appendix A Section 2.1: Specifications for Materials: Metals

In hydrogen technology, an essential issue is to make sure that all materials (i.e., typically metals) in contact with hydrogen are rated for hydrogen service. This is in the spirit of M-1002 where it is stated in Appendix A Section 2.1: Specifications for Materials: Metals: *"All devices covered by this appendix must be fabricated from materials that are resistant to corrosive or solvent action of the lading in the liquid or gas phase are suitable for the service temperature."* There is a technical gap between the M-1002 specification and hydrogen technology in that hydrogen embrittlement must be considered. At room temperatures, metals often used in hydrogen service are 316 or 316L stainless steel. These alloys have 10–14 percent Ni content and are thus expensive due to the cost of Ni. Embrittlement effects due to hydrogen are limited at cryogenic temperatures because the kinetics for hydrogen diffusion are greatly reduced. Pressures and therefore stresses are also reduced in LH_2 applications. Thus, the Ni content can be relaxed for material in contact with LH_2, such as 304 stainless steel which can have Ni content as low as 8 percent. Other metals that are appropriate for hydrogen service are aluminum and copper, since these do not suffer hydrogen embrittlement. Any storage vessel design needs to account for hydrogen embrittlement; vessels do not necessarily have to be limited to these specific metals, as long as the tank design itself accounts for the embrittlement that may occur. ASME B31.12 specifies additional requirements for hydrogen tank design.

As with any metallic vessel, corrosion must also be considered in addition to hydrogen embrittlement. NFPA 2 has many requirements for cathodic protection of containers and piping (e.g., Section 6.5.3.2.1 for piping in contact with earth), as well as explicit restrictions on corrosive chemical exposure (e.g., Section 7.1.9.1.7). Sections 8.1.3.1.7 and 8.1.3.1.8 address corrosion protections for LH_2 piping systems shall be protected against corrosion and cathodic protection where required be applied. ANSI/AIAA G-095A Section 6.1.1 mentions that corrosion resistance should be a consideration for materials selection. Section 6.2.4 addresses reducing the effects of hydrogen embrittlement, and that if aqueous exposure is a potential cathodic protection may be applied to prevent corrosion.

3.2.9 M-1002 Appendix A Section 3.13: Electrical Devices

An essential aspect of hydrogen safety is to make sure electrical devices within the tank car are rated for hydrogen service and are intrinsically safe. In M-1002, this is specified in Section 3.13: Electrical Devices*: "A car-mounted electrical device must be intrinsically safe for those parts of the device normally expose to the lading, and intrinsically safe or explosion-proof for those parts of the device not normally exposed to the lading if the lading is a flammable liquid, a flammable compressed gas…."* There is no technical gap here compared to the standards for safe hydrogen practice. Rather, it is called out here as being especially important for hydrogen service.

Section 8.3.1.2.6.2 of NFPA 2 states that where equipment approved for Class I, Group B atmospheres is not commercially available, the equipment used shall be purged or ventilated in accordance with NFPA 496 or intrinsically safe. Section 7.3.1 of ANSI/AIAA G-095A requires that equipment, wiring methods, and installations of equipment in hazardous locations be intrinsically safe, approved for the location, and safe for the location. Section 7.4.4 states that when equipment approved for Class I, Group B, atmospheres is not commercially available, the equipment may be one of the following: purged or ventilated in accordance with NFPA 496, intrinsically safe, or approved for Class I, Group C atmospheres.

3.2.10 M-1002 Appendix A Section 5.2.4 Flow Rate Test

It was stated previously (Section 3.2.7) that each PRD must be tested, which would seem to resolve the technical gap ambiguity concern raised in Section 3.2.2. However, in M-1002 Appendix A Section 5.2.4: Flow Rate Test: *"Tests must be made on pressure relief valves to determine the start-to-discharge pressure, vapor-tight pressure, and relieving capacity for each size, design and pressure setting. Tests must be made on a set of three pressure relief valves that are representative of production."* The research team believe there is a technical gap between this section and the earlier entry regarding PRD testing. There needs to be a clarification for what the PRD testing protocol is for each PRD, and how this is different from the current protocol concerning start-to-discharge pressure, vapor-tight pressure, and relieving capacity.

3.2.11 M-1002 Appendix C Section 2.3.3.1.2: Tank Qualification Inspection and Test

For corrosive fuels, it is good monitoring practice to test the fuel tank thickness. This is stated specifically in Appendix C Section 2.3.3.1.2: Tank Qualification Inspection and Test: *"For tank cars with an interior lining/coating (acting as a barrier between the base metal of the tank car tank and the commodity, including for product purity purposes), a tank thickness test is required at the time of application and removal/replacement of the interior lining/coating."* There exists a technical gap between this regulation and standard hydrogen practice. This regulation relies on measurements of tank thickness as an indicator of tank health. While this makes sense for corrosive products, it does not make sense for hydrogen which is not corrosive in the conventional meaning of corrosion. Due to the construction of LH_2 tanks, thickness measurements cannot practically be done, although it may be possible for non-cryogenic GH_2 tanks.

3.2.12 M-1002 Appendix E Section 3.0: Manway Covers

In specification M-1002, there is considerable discussion of the concept of "manways" which are ports allowing a person to go inside a tank to inspect it. The start of this discussion can be found in Appendix E Section 3.0: Manway Covers. There is a technical gap between this requirement for manways and the current hydrogen practice. For HP hydrogen tanks, the research team is unaware of any tank that has ever been made that allows reversible access to the inner tank space as described. For LH_2 tanks, there is a precedent. For example, Chart Industries made a large LH_2 tank for National Aeronautics and Space Administration (NASA) that has a manway enabling NASA technicians to access instrumentation within the inner liner. Short of this instrumentation need, there is no maintenance need to access the inner space of the tank once the tank is placed into service. For cryogenic tanks, such as for LH_2, a means of access could be mechanically created (e.g., cut or grinded) into the tank and repaired afterwards, rather than a removeable cover or hatch. For hydrogen applications, this regulation needs to be reconsidered. Neither NFPA 2 nor ANSI/AIAA G-095A has a similar requirement for access to the inner tank.

3.2.13 M-1002 Appendix E Section 15.0: Tank Appurtenances

In specification M-1002, there is a lot of technical detail concerning tank appurtenances (i.e., hardware accessories). This is stated in Appendix E Section 15.0: Tank Appurtenances. There lies an assembly of technical gaps between this section and the standard hydrogen practice. This section would have to be reviewed considering hydrogen technology hardware for both LH_2 storage and HP hydrogen storage.

Section 6.5.2.2 of NFPA 2 states that appurtenances serving hydrogen systems shall be accessible and shall be protected against physical damage or tampering. Sections 7.1.10 states that service and repair to tank appurtenances shall be performed by trained personnel and with permission of the container owner. Section 8.1.10 states that service, repair, modification, or removal of appurtenances shall be done in accordance with nationally recognized codes and standards. Section 16.2.2 states that all electrical installations including appurtenances shall comply with NFPA 70. Section 18.3.2.9.5.4 states that supporting structures of appurtenances used to support receivers shall be constructed of noncombustible materials and in accordance with adopted building code. ANSI/AIAA G-095A mentions appurtenances in passing in sections 8.4.8, 11.1.3, and G.2.4.

3.2.14 M-1002 Appendix L Section 1.1: Interior Cleaning, Lining and Coating

For current fuels used or carried on trains, there is a need for cleaning the interior of fuel tanks and the maintenance of interior linings. This makes sense for corrosive fuels, or fuels that can become fouled (e.g., diesel fuel). The M-1002 specification can be found in Appendix L Section 1.1: Interior Cleaning, Lining and Coating: *"Appendix L describes the AAR requirements for interior cleaning for, and the application and stripping of, interior linings and coatings for tank car tanks, valves, and fittings."* There is a technical gap between this specification and current hydrogen fuel storage practice. For either LH_2 tanks, or HP hydrogen tanks, there is no maintenance need for cleaning the tank interior. This is because the hydrogen fuel does not foul, and typically is introduced into the tank with high purity (i.e., 99.95% pure for H_2 gas, and 99.9999% pure for LH_2).

Section 7.3.5 of NFPA 2 requires that maintenance includes inspection for physical damage, leak tightness, ground system integrity, vent system operation, equipment identification, warning signs, operator information and training records, schedules maintenance and retest records, alarm operation, and other safety related features. It does not specify ongoing cleaning requirements. Section 6.22 of NFPA 2 addresses that hydrogen systems shall be cleaned and purged in accordance with Section 6.22, including cleaning and purging internal surfaces of hydrogen systems shall be conducted by qualified individuals, with clear written cleaning and purging procedures. Section 7.12 of ANSI/AIAA G-095A address examination, inspection, and recertification in accordance with ASME B31.3 or B31.12 for ground-based hydrogen pressure systems. It does not specify cleaning requirements.

3.2.15 M-1002 Appendix M Specifications for Materials

In hydrogen technology, it is critically important to have the right materials used for the hydrogen tanks and associated plumbing. This is in the spirit of M-1002 in Appendix M Specifications for Materials. There exists a technical gap between these listed material choices and the proper ones for hydrogen service. The same comments and concerns apply in Section 3.2.8.

3.2.16 M-1002 Appendix M Section 4.6.2: Miscellaneous Tank Materials

For hydrogen service, the right metal alloys need to be chosen. This is consistent with the M-1002 specification in Appendix M Section 4.6.2: Miscellaneous Tank Materials*: "For stainless steel appurtenances on carbon steel tanks, low carbon grades of stainless steel (304L, 316L) are recommended."* There is a technical gap between this specification and standard industry hydrogen practice. Alloy 316/316L can always be used for hydrogen service, but 304/304L is not recommended for hydrogen service at room temperature. Again, this is related to Section 3.2.8.

3.2.17 M-1002 Appendix T Section 3.0: Leak Testing

Leak checking is the foundation of the safe use of hydrogen. In any hydrogen fuel cell system, there are many connections made between the tank and various components. These connections need to be leak checked on a regular basis using a combustible gas detector, especially if the hydrogen technology is subject to shock and vibration as in the rail environment. The concept of leak checking is specified in M-1002 in Appendix T Section 3.0: Leak Testing. In the requirements table (in Appendix T Section 3.1), the "acceptable test sensitivity or leakage rate" is indicated as being a requirement for written procedures, but it is not stated what the target leak rate number is. This represents an important technical gap relative to the current safe hydrogen practice. Test sensitivity for leaks is important to leak checking acceptability, and to minimize safety hazards.

NFPA 2 does not specifically state an acceptable leak rate for approval. Section 10.4.5 requires that hydrogen dispensing systems shall be leak tested after final installation and in addition testing is required by ASME B31 Code for Pressure Piping. Section 10.4.5.4 specifically states that the leak test should be using hydrogen for GH_2 vehicle fueling facilities. Other sections recommend initially using an inert gas before using hydrogen. Section 10.3.1.10 addresses leak testing for LH_2 fueling facilities. The section requires that the system shall be leak tested using hydrogen or helium and be purged with inert gas prior to the leak test to ensure all oxygen is removed. Section 7.12.3 in ANSI/AIAA G-095A requires that a hydrogen system shall be leak tested prior to operation and states, if possible, an inert gas be used before LH_2 is introduced into the system. Section 8.3.1 addresses piping systems that leak testing shall be done in accordance with ASME B31.12 or ASME B31.3.

3.3 Hydrogen Applicability Gaps for AAR MSRP Section M

The AAR MSRP Section M covers the design of locomotives and has been reviewed for its applicability and relationship to potential hydrogen-fueled rail technology. Hydrogen fuel cell powered locomotives would likely be designed very differently than traditional diesel electric locomotives, and so would require a completely new standard to be written to account for this. Unlike natural gas, hydrogen would likely not operate in a dual-fuel combustion engine with diesel; rather, hydrogen fuel cells would provide the electric power for the locomotive. Since there would no longer be any diesel fuel on this new type of locomotive, the currently written AAR MSRP Section M would not apply. However, the research team reviewed this standard for hydrogen applicability to identify significant differences that would need to be modified in a new locomotive standard for hydrogen fuel cells. Of particular interest, are the need for electronic rack ventilation, the location of fuel tanks beneath the underframe, and the need for breakaway fueling lines.

3.3.1 S-590 Section 3.1.1.3: The Locomotive and Train Support Electronics Subsystem

Section M discusses the overall locomotive electronics logical architecture overview in S-590 Section 3.1: Locomotive Electronics Logical Architecture, and more specifically Section 3.1.1.3 where it is stated*: "The Locomotive Control subsystem contains functions that relate to locomotive control operations and that typically are required to provide motive power or dynamic brake lead or trail locomotive in a consist. Examples of Locomotive Control subsystem functions include adhesion control, engine cooling control, and traction motor thermal protection."* There is a technical gap between this document and hydrogen fuel cell technology due to the different control electrical architecture of PEM fuel cells. Each individual cell in a fuel cell stack can be monitored for voltage and current, and the monitoring of these quantities is part of any fuel cell control system. So, the locomotive electronics logical architecture must reflect this feature of PEM fuel cells. Neither NFPA 2 or ANSI/AIAA G-095A address locomotive electronic architecture or PEM fuel cells.

3.3.2 S-590 Section 4.2.14: Fuel Tank Monitor (FTM)

The monitoring of fuel level is important for any technical application involving fuel. This is noted in S-590 Section 4.2.14: Fuel Tank Monitor (FTM), where it is stated: *"The Fuel Tank Monitor object shall supply the fuel tank depth to other locomotive objects via the locomotive LAN."* There is a technical gap here between the Section M language and hydrogen fuel cell technology. For HP storage of hydrogen gas, there will be a tank pressure and temperature reading that must be converted to a "fuel remaining" indicator. That fuel remaining indicator will have to take into account that one never wants to deplete the hydrogen tank in a HP tank to zero-gauge pressure, to maintain positive pressure relative to the environment (e.g., 100 psig). For LH_2 storage of hydrogen, there is a depth that can be indicated and converted to a "fuel remaining" indicator. As with HP hydrogen, one always wants to leave some LH_2 in the tank (e.g., ~5) so the tank remains cold to aid in the refueling of the tank from a LH_2 delivery trailer. These details must be accommodated by a revised Section M document that covers hydrogen fuel cell technology.

Section 7.11 of ANSI/AIAA G-095A addresses instrumentation and monitoring for hydrogen systems. It broadly requires that the system should be adequately instrumented to monitor control of operation, provide performance data, provide warning and/or alarms for nonstandard operating conditions, indication for hazardous conditions, and requires that instrumentation meet NFPA 70 requirements as applicable. Instrumentation should be compatible with all operating temperatures and pressures for hydrogen, local and/or remote operation and monitoring of the system, and have appropriate range, accuracy, and response time. Additionally, instrumentation should be redundant in number and types of transducers. Specifications for fire detection is detailed in Section 7.11.3 primarily discussing the ability to detect the signatures of a hydrogen fire using a combination of fixed and portable hydrogen fire detectors that meet NFPA 70 as appropriate. Section 8.3.4.6 of NFPA 2 requires a pressure gauge and full trycock valve and shall be visible from the delivery point allowing the operator to monitor internal pressure and liquid level of stationary containers during filling. Neither standard contains a minimum gauge pressure that should remain in a tank.

3.3.3 S-590 Appendix E Section 1.2: Overview

Any technology that incorporates electronic components must consider thermal management of said electronic components. In Section M, this is stated in S-590 Appendix E Section 1.2: Overview: *"There is a desire to maintain acceptable operating temperatures of the electronics inside the cabinet without the benefit of forced convection. Forced convection can be construed as any induced air movement, either by cooling fans, locomotive movement or any other methods involving mechanical techniques."* A hydrogen fuel cell can be considered an electronic component—as it produces, conditions, and distributes electricity—there exists a technical gap between the Section M language and hydrogen fuel-cell technology. Hydrogen PEM fuel cells typically consist of individual power modules which are stacked together into racks. The rack itself is typically ventilated with a constant flow of air, in addition to having a hydrogen detector within the rack. If the fuel-cell rack is placed in a room within the locomotive, then the "fuel-cell room" itself should be actively ventilated. This may not be the case if the fuel cell is located on the roof of the locomotive, out in the weather. In any event, the "without forced convection" language of Section M should be modified to cover the realities of hydrogen fuel-cell technology.

Section 6.20 of NFPA 2 addresses ventilation requirements for exhausted enclosures, requiring that the exhaust ventilation system is designed to operate at negative pressure in relation to the surrounding area. Sections 6.5.2.3, 6.19.2, and 8.3.1.2.4.3 reiterate the requirement that cabinets or enclosures shall be ventilated to prevent hydrogen accumulation and reiterates that exhaust ventilation operate at negative pressure in relation to surroundings. Section 7.4.2 of ANSI/AIAA G-095A addresses cabinets or hood systems in laboratory settings (e.g., small inventories of hydrogen) have ventilation rates between 50 and 150 ACH. Section 8.2.1 states that valve cabinets shall be well ventilated. Neither standard directly discusses the forced convection or other mechanical techniques for the stated purpose of maintaining acceptable operating temperatures within electrical cabinets.

3.3.4 S-591 Section 1.0: Locomotive System Integration Operating Display

Locomotive system operating displays are critical for operational safety. This is indicated in Section M S-591 Section 1.0: Locomotive System Integration Operating Display Standard S-591, where it is stated that Standard S-591 *"defines the basic requirements for an industry standard visual display of locomotive operating information."* There is a technical gap between this Section M language and hydrogen fuel-cell technology. The use of a PEM fuel cell brings a whole new level of display information, because each cell within a PEM stack can be individually monitored. PEM fuel cells typically have extensive visual operating systems. Hence, Standard S-591 will need to be modified to account for this. It could be that only summary or specifically relevant information will be included in the on-locomotive display, with the remainder of the information being monitored elsewhere.

Neither NFPA 2 or ANSI/AIAA G-095A address a fully integrated control room or display system. NFPA 2 does require visual indication and warning systems for the various systems i.e., oxygen level, ventilation rates, temperature, pressure, fire protection, flow rates, and procedures. Section 7.5.1 of ANSI/AIAA G-095A addresses the requirements for control rooms briefly requiring that all hydrogen systems should provide a visual means of observation via direct or closed circuit television.

3.3.5 S-5506 Section 2.0: Background Performance Requirements for Diesel Electric Locomotive

The placement of fuel tanks is a critical issue for diesel locomotives and will be an important reliability and safety issue for hydrogen-powered trains as well. In Section M S-5506 Section 2.0: Background Performance Requirements for Diesel Electric Locomotive Fuel Tanks: *"By virtue of their location beneath the underframe and between the trucks, the locomotive fuel tanks are vulnerable to damage from impact during a derailment or collision or by debris and loose equipment on the road bed."* The regulations do not consider moving the location of diesel fuel tanks, rather they specify the tank puncture resistance, with the understanding that *"The complete elimination of fuel spills under the most severe accident conditions is considered to be impractical."* The location of the diesel fuel tanks represents a technical gap between the Section M regulations and the practical implementation of hydrogen technology. Neither GH_2 nor LH_2 tanks should be integrated into the locomotive design by placing them underneath the locomotive underframe due to the smaller volumetric storage density of hydrogen compared to diesel—which makes the tanks larger—and the composite (GH_2) or vacuum shell (LH_2) design which makes them structurally more vulnerable. GH_2 and LH_2 tanks could be placed on top of the locomotive roof, which also promotes vertical dispersion of hydrogen upon inadvertent release.

Neither NFPA 2 nor ANSI/AIAA G-095A address the specific location of the hydrogen tank in relation to train frame. These standards address fixed-location hydrogen tanks. Section 7.1.4.2.1.2 addresses motorized equipment and states that storage systems shall be installed that protect valves, pressure regulators, fittings, controls against accidental impact, and not extend beyond the platform of the mobile equipment. Section 7.2.4.2.2 states that cylinder, containers, and tanks moved by mobile devices shall be designed to secure the movement of the tank. Section 11.3.5 of ANSI/AIAA G-095A requires recertification for mobile vessels shall be done in accordance with 49 CFR § 180.407.

3.3.6 S-5506 Section 4.1: Design Considerations

The type and location of the fuel tank drive many load test requirements for locomotives. For example, in Section M S-5506 Section 4.1.1–4.1.3, there are crashworthiness specifications for diesel fueled tank for minor derailment, a jackknifed locomotive, and a side-impact crash. This group of specifications represents a technical gap relative to hydrogen technology because the crashworthiness of a hydrogen tank (HP or LH_2) located on the roof of a locomotive is expected to be different than for placement of the fuel tank beneath the underframe.

3.3.7 S-5506 Section 4.4: Fueling

Tank structural stability is an important safety and maintenance issue for the high fueling rates encountered in the rail environment. Section M S-5506 Section 4.4: Fueling states: *"Internal structures of the tank must not impede flow of fuel through the tank while fueling at a rate of 300 gallons per minute."* On an equivalent lower heating value (LHV) basis, this would correspond to 341 kg H_2/minute. There may exist a technical gap, not between the Section M specification and hydrogen technology, but rather between the 341 kg H_2/minute fueling rate and existing commercial hydrogen delivery rates. Liquid hydrogen transfer pumps can have very different flow rates, and gaseous hydrogen compressors vs. fast-fill pressure cascade systems can all have widely disparate flowrates. Depending on the fueling time desired, commercial availability of hydrogen transfer times, and other factors, this flow rate may need to be changed for hydrogen locomotives.

3.3.8 S-5511 Section 6.0: Vibration Laboratory Tests

Vibration and shock testing at the technical operating temperatures are important for implementation of any technology in the rail environment. Section M S-5511 Section 6.0: Vibration Laboratory Tests states: *"TOR (top of rail) application systems should be screened using TTCI's laboratory vibration test matrix."* There appears to be a technical gap between this Section M regulation and the prospects of using LH_2 in the rail environment. Since the temperature of hardware in LH_2 technology can range from 20 K (-423 °F) to 330 K (134 °F), there is a need for shock and vibration testing at low temperatures. It is possible that testing the LH_2 technology at the more convenient and cost-effective 77 K (-321 °F) temperature of LN_2 is possible and would capture the essential physical phenomena, but this would have to be evaluated. Neither NFPA 2 or ANSI/AIAA G-095A address vibration test requirements or matrix, since they are specific to fixed-facilities.

3.3.9 S-5511 Appendix A Locomotive Component Laboratory Test Procedure

Vibration and shock testing for extended periods are critical to certify rail technology components. In Section M it is given in S-5511 Appendix A Locomotive Component Laboratory Test Procedure; Section 1.3 of Appendix A gives a good account of what they are looking for in vibration testing. There is, however, a technical gap between Section M and LH_2 hydrogen technology because Appendix A does not specify low temperature cryogenic testing which would be necessary for LH_2 storage of hydrogen.

3.3.10 RP-503 Section 3.0: Fuel Property Tests

Diesel fuel properties can vary depending on the source, and with the presence of additives. In Section M this appears in RP-503 Section 3.0: Fuel Property Tests where it is stated in Section 3.1: *"The following physical and chemical fuel properties (appearing in nearby Table 3.1) shall be reported for both a sample of diesel fuel and a sample of the same diesel fuel treated with the additive in the manner recommended by the additive manufacturer…. The purpose of these tests is to evaluate effects of the additive on limiting fuel specification requirements."* There is a technical gap between this Section M specification and hydrogen technology. Such a fuel purity specification will not be needed for H_2 rail technology because LH_2 and GH_2 are quite pure (> 99.95% pure for GH_2, 99.9999% pure for LH_2). There are also no additives in hydrogen fuel.

3.3.11 RP-503 Section 5.0: EMD 2-567C Engine Test

Diesel emissions are a major environmental concern for locomotives. This is addressed in RP-503 Section 5.0: EMD 2-567C Engine Test and subsequently in Section 5.2 where it is stated: *"Gaseous emissions measurements shall be made in accordance with the Federal Test Procedure, Federal Register, Vol. 42, Number 174. Smoke opacity (steady-state) shall be measured at each load-speed point using the equipment (USPHS smokemeter or equivalent) and equipment calibration procedures specified in the Federal Test Procedure."* In Section 5.3 it is specified, "*Hourly readings should be taken of all engine performance data, including exhaust smoke opacity. Exhaust emissions (including particulates) should be measured once approximately mid-way through the test sequences for both baseline and additive-treated fuels.*" These Section M specifications on diesel engine emissions represents a technical gap with hydrogen PEM fuel-cell power because PEM fuel cells are zero-emission power plants that emit no criteria pollutants or GHG emissions. As a result, all gaseous emission tests, as indicated in Section 5.2, will not need to be carried out with H_2 fuel-cell technology.

3.3.12 RP-503 Appendix C Detection of Nitrate-type Ignition Improvers in Diesel Fuel

There are various additives that can be added to diesel fuel to improve performance. For example, Section M RP-503 Appendix C Detection of Nitrate-type Ignition Improvers in Diesel Fuel states: *"This method of test covers the determination of organic nitrate ester-type cetane improver additives used in diesel fuel. It is intended as a screening test for those diesel fuel inspection test procedures that are affected by the presence of cetane improvers."* This represents a technical gap between Section M and hydrogen technology because there are no additives needed for hydrogen to be use in PEM fuel cells. As an aside, any additive would likely have deleterious effects on the catalysts found in PEM fuel cells, as well as the PEM material.

3.3.13 RP-557 Spark Arrester Recommended Practice

Diesel engines are known to be significant sources of greenhouse gas and criteria pollutant (smog) emissions. They also exhaust the products of incomplete combustion (hot ash) which is a fire hazard. Section M describes RP-557 Spark Arrester Recommended Practice. A spark arrestor is a mechanical device to keep hot debris coming from diesel combustion coming out of the exhaust and setting surrounding grasslands on fire. This represents a technical gap between Section M and hydrogen PEM fuel cell technology. Since there is no combustion inside a fuel cell, and the only emissions are warm humidified air and some liquid water, a spark arrestor is not needed for H_2 fuel-cell technology.

Section 7.3.5.5 of ANSI/AIAA G-095A mentions that internal combustion systems, motor vehicles, or equipment employing internal combustion engines shall be equipped with exhaust system spark arrestors and carburetor flame arrestors (i.e., hydrogen approved) when operated within the exclusionary zone with hydrogen present. NFPA 2 does not address spark arrestors.

3.3.14 RP-5503 Section 2.1.2: Basic Fueling Requirements

Overfill protection is an important part of any fuel-based transportation system. This is noted in Section M RP-5503 Section 2.1.2. Basic Fueling Requirements: *"The fueling system will provide overfill protection…"* There is a technical gap between Section M and standard hydrogen practice concerning overfill protection. The fueling system diagram found in Figure 2.1 ("Basic Locomotive Fueling System Interface") is ambiguous with regard to overfill protection. It does not clearly indicate, from a hydrogen fueling perspective, where the system overfill protection resides, on the locomotive or on the fueling facility (or truck). This ambiguity must be resolved for hydrogen use on rail. For light-duty hydrogen fuel-cell vehicles, the overfill protection is provided by the hydrogen station, and is not the responsibility of the technology resident on the fuel cell vehicle.

Section 7.3.2.4.10 of NFPA 2 states that an approved means or method shall be provided to prevent overfilling of storage containers. Section 8.1.5.5 states that controls shall be provided to prevent overfilling of stationary containers and Section 8.3.4.5.10 mentions similar requirements. NFPA 2 does not specify the responsible party for overfill protection either the technology or hydrogen station. ANSI/AIAA G-095A does not address overfill protection measures.

3.3.15 RP-5503 Section 2.1.2: Commentary

One of the primary benefits of hydrogen fuel-cell technology, compared to battery technology, is that if a problem develops, hydrogen fuel can be shut off to the fuel cell, dramatically reducing the energy available to an accident or problem, thereby increasing safety. This requires clear specification on how this fuel stoppage occurs. Section M RP-5503 Section 2.1.2: Commentary notes: *"The characteristics of the equipment (e.g. electrically operated gate valves) used to interrupt the flow of fuel under control of the signal interface are not covered in this recommended practice because they are dependent upon the equipment used by the fueling site."* This represents a technical gap between Section M and standard safe hydrogen practice. How hydrogen flow stoppage occurs on the locomotive needs to be clearly defined for hydrogen refueling.

Section 10.3.13.1 of NPFA states that the activation of detection systems shall automatically stop dispensing and activate the automatic emergency shutoff valve. Section 10.5.1.1.5.1 states the protection shall stop the dispensing of hydrogen if the dispenser pressure or dispenser fuel temperature deviate from operating parameters. Section 11.3.1.8 states that an emergency shutdown system shall be provided that includes a shut-off valve provided within 10 feet of the dispenser. Section 10.5.1.3.3 and 15.3.1.1.7.2 reiterate the automatic shutoff if operating parameters are deviated from. Section 8.5.2 of ANSI/AIAA G-095A mentions requirements for where stop valves should and should not be installed. Sections 12.4.2 and 12.4.3 state that hydrogen systems shall be designed to stop gas flow in an emergency.

3.3.16 RP-5503 Section 2.2.1.4: Drive-off Protection

As with other ground-based transportation, it is very important to mitigate the damage and fuel release that can occur when there is large unplanned movement between the refueling line and the locomotive (i.e., a drive off scenario). In Section M, this is discussed in RP-5503 Section 2.2.1.4: Drive-off Protection: *"Recommendation: In the interests of limiting fuel spillage resulting from drive-off accidents, the fuel delivery line should be designed with breakaway joints or other features that limit the loss of fuel resulting from such accidents…."* This may represent a technical gap between Section M and LH_2 technology. While HP hydrogen refueling lines have the option of such a breakaway piece installed in the hose line, such technology may not be commercially available for LH_2. A cryogenic breakaway does exist for other cryogenic fluids such as LNG, LN_2, and liquid argon, but the research team has not found a commercially available breakaway line for LH_2 as of yet. Given the similar temperatures for LN_2 (77 K) and LH_2 (20 K), it is likely current technology could be reasonably extended to handle the LH_2 breakaway line problem.

Section 10.3.7.6 of NFPA 2 mentions that a breakaway device that causes hydrogen gas flow to stop shall be installed between the connection of the hose to the dispenser and the filling nozzle. When a separate vent hose is used, the vent hose connection shall also be equipped with a breakaway device. Section 10.3.7.6.2 states that other connections shall not prevent the operation of the gas flow breakaway device. Sections 10.8.3 and 11.3.1.11 list similar requirements regarding breakaway devices. Other sections throughout the standard list maintenance and test requirements for breakaway devices to ensure that they work appropriately. ANSI/AIAA G-095A does not address breakaway devices.

3.3.17 RP-5503 Section 2.2.2.1: Maximum Pressure Drop

The physical state of hydrogen, being a gas for almost all temperatures except for inside an LH_2 tank, makes it physically different than diesel fuel with regard to system pressures. Control of pressure is very important for diesel locomotives. In Section M, this is indicated in RP-5503 Section 2.2.2.1: Maximum Pressure Drop. This represents a technical gap between Section M and the physical realities of hydrogen as a fuel. The pressure drop specifications written for diesel fuel are not applicable for hydrogen refueling (HP or LH_2) and should be re-evaluated and rewritten.

3.3.18 RP-5503 Section 2.5.3: Proof Pressure

The physical state of hydrogen, being a gas for almost all scenarios except for inside an LH_2 tank or LH_2 transfer piping/hoses, makes it physically different than diesel fuel with regard to system pressures. Another example of system pressure control for locomotives occurs in Section M in RP-5503 Section 2.5.3: Proof Pressure, where it is stated: *"The seal between the nozzle and the* *fuel receptacle, when the two are connected for fueling, shall withstand an internal proof pressure of up to 50 psi at the plane of coupling without leakage of fluid."* This represents a technical gap between Section M and the physical realities of hydrogen as a fuel, particular HP hydrogen where the pressures can be as high as 700 bar (10,153 psi). All the pressure specifications in Section M should be re-evaluated and rewritten for H_2 rail technology. Neither NFPA 2 or ANSI/AIAA G-095A address or mentions proof pressure requirements, although other design standards (e.g., ASME B31 and vehicular standards like GTR 13) do include these types of requirements.

3.3.19 RP-5503 Section 2.7: Support Requirements

Hydrogen use in a rail environment will change the way that maintenance is performed. The issue arises in Section M RP-5503 Section 2.7: Support Requirements where it is stated in subsection 2.7.1.1: *"The components of the locomotive fueling system shall be designed to permit an operator to perform routine maintenance with minimal training."* This represents a technical gap between Section M and current hydrogen practice. Currently, if a delivery truck is providing hydrogen, the company providing the hydrogen will be responsible for maintenance up to the receptacle on the locomotive hydrogen tank. Similarly, only qualified representatives are permitted to perform maintenance on refueling facilities or other systems. Due to the consequence of a large hydrogen system release, likely only specifically qualified individuals will be permitted to do maintenance.

Section 7.3.5 of NFPA 2 addresses maintenance requirements for bulk GH_2 systems, primarily that maintenance shall be performed annually by a qualified representative of the equipment owner. The section goes into detail into what should be inspected and tested and documented. Section 6.13.2.1 of NFPA 2 states that maintenance, inspection, calibration, and testing shall be conducted by trained personnel for GH_2 detections systems. Section 7.1.17.4 states that maintenance of cathodic protections systems shall be done under the supervision of a corrosion expert certified by the National Association of Corrosion Engineers (NACE). Chapter 8 of NFPA 2 for LH_2 outlines similar requirements for maintenance specifically Section 8.3.5 stating that it should occur yearly by a qualified representative of the equipment owner. Section 10.6 states that hydrogen dispensing systems shall be maintained in accordance with the manufactures' instructions. The section goes on specify maintenance for various components. Section 11.2.14 discusses more maintenance requirements for LH_2 fueling facilities. ANSI/AIAA G-095A does not specifically address maintenance requirements, it does mention the need for maintenance during the lifecycle of hydrogen facilities.

3.3.20 RP-5503 Section 2.8: Fuel Nozzle Clearance

Hardware compatibility between refueling source and the locomotive is important for smooth, safe and reliable refueling operations. An example of this is in Section M RP-5503 Section 2.8: Fuel Nozzle Clearance: where it is stated *"The fuel nozzle, including attached handles, levers, and similar features, shall not exceed a 5.25-in. radius around the centerline of the fuel receptacle, within 6 in. of the nozzle-sealing surface."* This statement may represent a technical gap between Section M and current hydrogen practice. The size specified for the fueling nozzle may have to be revised to larger sizes to accommodate the hydrogen nozzle hardware, for either HP hydrogen or LH_2, than can accommodate the required hydrogen refueling. Neither NFPA 2 or ANSI/AIAA G-095A addresses specific nozzle size requirements or clearances, although dispenser nozzle dimensions and designs are specified in fueling protocols (e.g., SAE J2601).

3.3.21 RP-5503 Section 4.1.1: Minimum Ullage Space

Ullage represents the amount by which a container falls short of being full. Fuel tanks usually have minimum ullage defined so as not to overfill during refueling, or to accommodate fuel expansion with heating. This is indicated in Section M RP-5503 Section 4.1.1: Minimum Ullage Space: *"The fueling system shall be designed to leave a minimum ullage in the locomotive tank of 200 gal, or 4% of total tank capacity, whichever is smaller."* This represents a technical gap between Section M and hydrogen fuel technology. Ullage has no meaning for a HP hydrogen tank but does have a meaning for LH_2 tanks. For LH_2 the minimum ullage will likely be larger than the 4 percent mentioned. This is an area of regulatory development for maritime LH_2 tank technology, how small in ullage you can go. It is currently at 25 percent for LNG for maritime applications, and it would be good to go lower if possible, to get more fuel in the tank during a given refueling operation.

Neither NFPA 2 nor ANSI/AIAA G-095A state a specific minimum ullage space. NFPA 2 does state in Section 11.4.3.1 that all cryogenic containers, vessels, and tanks shall provide and maintain ullage space to prevent over-filling of the vessel. Section 10.2.3 of ANSI/AIAA G-095A states that overloading the vessel reduces ullage space and may result in leakage and unwarranted thermal cycling which could results in the relief valves becoming inoperable.

3.3.22 RP-5503 Section 5.2.1: Fouling/Varnish Test

Diesel fuel itself, as well as the contaminants contained therein, can lead to fouling and varnish of fuel level sensors. This is indicated in Section M RP-5503 Section 5.2.1: Fouling/Varnish Test where in Section 5.2.1.1 it is stated: *"Lengthy exposure of the high-level sensor to fuel oil, combined with chemical or mechanical action, can lead to a buildup of varnish-like material on the sensor."* This represents a technical gap for Section M compared to existing hydrogen technology. Since both HP hydrogen and LH_2 are very pure substances (i.e., industrial grade HP hydrogen is 99.95% pure and LH_2 is 99.9999% pure) there is no fouling or varnishing of sensors or any other part of the fueling system caused by exposure to hydrogen fuel, so long as the sensors are rated for hydrogen service. A standard such as CGA PS-56 does address inspecting of LH_2 tanks.

3.3.23 RP-5503 Section 5.2.3: Foam Test

Agitation of diesel fuel can produce foam which might confuse fuel level sensors. The issue is brought up in Section M RP-5503 Section 5.2.3: Foam Test where it is stated in Section 5.2.3.1: *"Under certain circumstances, the agitation of fuel inside the tank can lead to the buildup of a foam layer on top of the liquid."* This represents a technical gap between Section M and hydrogen technology because neither HP hydrogen, nor LH_2, foam when agitated.

3.3.24 RP-5503 Section 5.3.2: Leakage Tests for Receptacle and Nozzle

Pressure testing of fueling interface hardware is important to prevent unsafe fuel spillage. For example, in Section M RP-5503 Section 5.3.2: Leakage Tests for Receptacle (5.3.2.1) and Nozzle (5.3.2.2), it is stated: *"The outlet of the receptacle, with its cap removed, shall be subjected to 50-psi internal pressure of reference fuel for a period of 10 min"* (5.3.2.1), and *"The* *closed nozzle shall be subjected to an internal pressure of 240 psi for a period of 10 min"* (5.3.2.2). There is a technical gap between the pressures listed in this specification, and the test pressures that will be required for the use of HP hydrogen tanks, which could be storing hydrogen, and be refueled by hydrogen trailers, with pressures ranging from 240–700 bar (3,481–10,153 psi). The required test pressures will need to be determined for the hydrogen rail application.

Section 10.5.1.1 of NFPA 2 addresses vehicle fueling dispenser system operation. Requiring systems shall be designed to verify the integrity of the fuel hose, breakaway, nozzle, and receptacle by pressurizing these components to at least the vehicle back pressure and monitoring pressure decay for at least five seconds before initiating fueling. Section 10.5.1.1.2 addresses specific numeric values that shall be met. ANSI/AIAA G-095A mentions pressure testing in passing in Sections 7.12.3 and 8.4.6 but does not get into specific numeric requirements.

3.3.25 RP-5503 Section: 5.3.2.4 Spillage

For current diesel locomotives, there are regulations on the amount of fuel that can be allowed to be spilled during fueling connects and disconnects. This is altogether appropriate, because diesel fuel is a toxic substance which can cause environmental damage even in the absence of a fuel fire. This is covered in Section M RP-5503 Section 5.3.2.4: Spillage where it is stated in subsection 5.3.2.4.1: *"The amount of liquid that is lost during a disconnect (i.e., that is left inside the nozzle-receptacle joint after disconnect) shall be collected and measured (by volume) on at least 10 disconnect cycles. The average value shall be less than 5 cm^3 across all trials."* This represents a technical gap relative to HP and LH_2 hydrogen technology. The problem arises from the physical properties of hydrogen. While is relatively easy to collect liquid diesel fuel, handle it, and measure it, hydrogen is a highly dispersive gas. It would be difficult to capture and measure hydrogen gas as envisioned by this Section M specification. The need to measure spillage is reduced for hydrogen because, unlike diesel fuel, hydrogen is non-toxic and is not an environmental hazard. There should be an investigation of how this specification is applied to LNG technology. Natural gas is less dispersive than hydrogen and LNG requires more heat to evaporate than LH_2. Both properties make NG easier to comply with this Section M language regarding spillage.

Section 6.15 of NFPA 2 addresses the need for spill control, drainage, and secondary containment. The section states that spill control, drainage, and secondary containment shall not be required for GH_2 systems. Section 8.3.2.1 states the that diking shall not be used to contain LH_2 spills but can be used to direct a spill away from potential exposures. ANSI/AIAA G-095A discusses hydrogen spillage throughout the standard and the characteristics of hydrogen spills and potential ramifications of spills. Section 7.8.2 states that site specific information should determine whether natural dispersion or confinement of the spill is preferred. Section 12.2.3 states if an uncontrollable leak occurs that an area of 500 feet shall be evacuated from the spill source. Neither standard addresses spillage directly regarding nozzle spillage nor a specific quantity allowed.

3.3.26 Section 5.3.6: Vibration and Shock

Section M specifies the need for vibration and shock testing of refueling receptacles and nozzles. This is stated in RP-5503 Section 5.3.6: Vibration and Shock, subsection 5.3.6.1: *"The nozzle and receptacle, disconnected and closed, shall be mounted in separate fixtures and subjected to* *sinusoidal vibration (as defined in ATCS Specification 110, paragraph 3.2.4.1),"* and also in subsection 5.3.6.2: *"The nozzle and receptacle, disconnected and closed, shall be mounted in separate fixtures and subjected to random vibration (as defined in ATCS Specification 110, paragraph 3.2.4.2),"* and finally in subsection 5.3.6.3: *"The nozzle and receptacle, disconnected and closed, shall be mounted in separate fixtures and subjected to mechanical shock (as defined in ATCS Specification 110, paragraph 3.2.4.3)."* This represents a technical gap with current hydrogen technology practice. The need for vibration/shock testing for the receptacle is clear, as it resides on the locomotive and subject to the vibration/shock of the rail environment. However, the nozzle will typically stay with the refueling hose on the hydrogen delivery trailer, or at the stationary hydrogen refueling infrastructure. The research team notes here that Section M does not specify vibration/shock testing of the hydrogen tanks (HP or LH_2) which will be needed and requires definition.

3.4 Discussion of Hydrogen Applicability Gaps

The document-specific preceding sections give a full review of the documents for hydrogen technology applicability. Here the research team provides a summary of the major findings from these reviews, grouped and summarized according to technical topic.

3.4.1 Ventilation

Ventilation can be defined as the provision of fresh air to a room or space. Ventilation is critically important for the safe use of a flammable gas such as hydrogen or natural gas, because ventilation acts to dilute the flammable gas to concentrations below the LFL and removes the fuel/air mixture from the room or space. In laboratories that use hydrogen, there is either continuous active (forced) ventilation or the forced ventilation is triggered if a hydrogen alarm is sounded. In maritime uses of hydrogen on vessels, continuous forced ventilation of the room containing a fuel cell is an important safety provision. In some applications, the rack containing the fuel cells is independently actively ventilated, with the rack contained within a room that is itself actively ventilated. Also, in the maritime setting, the plumbing connections emanating from a tank containing a flammable gas or liquid are housed within a tank connection space which is actively ventilated. By contrast, the AAR regulations recommend electronic racks to be passively ventilated. This avoidance of forced ventilation needs to be revised not only for rail electronic components, but also fuel cell assemblies and for the enclosed spaces fuel cell technology may find itself in in a rail environment.

3.4.2 Fuel Tank Location

Hydrogen fuel tanks are very different than diesel fuel tanks. Diesel fuel tanks are typically made from steel, are relatively simple in construction and very robust in deployment. A typical 250-gallon diesel fuel tank is constructed from 11-gauge (1/8" thick) steel. Larger tanks have even thicker walls and can be double-walled. Locating diesel tanks beneath the underframe of a locomotive is entirely reasonable and the underframe location has been successfully used for decades. Hydrogen tanks are more complicated, with the complexity arising due to the need to contain high-pressure gaseous hydrogen (up to 700 bar) or limit heat ingress into a very cold (20 K) supply of LH_2 that is easily evaporated.

Gaseous hydrogen can be stored in robust steel tanks (Type 1 pressure vessel), lighter-weight carbon-fiber-wrapped aluminum liners (Type III pressure vessel), or even lighter still, carbon-fiber-wrapped plastic liners (Type IV pressure vessel). Commercial LH_2 tanks are constructed of an inner vessel (typically stainless steel) surrounded by a carbon steel outer vessel, with vacuum and insulation in the annular space between the two vessels. While the heavy steel Type 1 hydrogen tanks could potentially be placed below the undercarriage, the lighter Type III and Type IV would be more sensitive to debris impact from the tracks and should not be located beneath the underframe. Although the outer carbon steel vessel of LH_2 tanks is robust, debris impacts from the track could induce relative motion between the inner and outer vessels which is better avoided to prevent damage to the supporting structure and insulation. Since room-temperature hydrogen, once leaked, is highly buoyant in air and will rise straight up, it makes more sense from a gas dispersion perspective to have the hydrogen tanks higher in the locomotive structural design.

3.4.3 Vibration Testing

The level of vibration and shock experienced in the rail environment is significantly higher than other environments in which hydrogen fuel cells have typically been used (e.g., light-duty vehicles, stationary applications, etc.). In addition, rail crash scenarios involve shocks and penetrations that are also beyond typical fuel cell applications in the past. This makes vibration testing of all aspects of hydrogen fuel cell technology (e.g., tanks, plumbing, diagnostics, fuel cell assemblies) critically important. If LH_2 is involved, then it is important that such testing be conducted at or near the cryogenic temperatures that the equipment will experience in use. There seemed to be no AAR document specifying the shock/vibration testing a locomotive diesel engine itself must go through; this seems like it could be an omission, but hydrogen systems and fuel cell electronics would certainly need to undergo shock and vibration testing.

3.4.4 Fueling

The fueling of trains, cars, boats, and other mobile technology all suffer from a single problem in fueling: the train, car or boat might leave the fueling station while the refueling is in progress. Hence the need for breakaway devices on fueling lines to avoid drive-off accidents. Diesel and gasoline fueling lines have breakaway devices that prevent significant fuel loss or spill during a drive-off accident. The same is true for CNG and LNG fueling lines. Breakaway devices do exist for gaseous hydrogen refueling lines, but it is not clear that breakaway lines are commercially available for LH_2. However, they do exist for other cryogenic fluids such as liquid nitrogen and LNG which could probably be adapted or modified in a straightforward way for LH_2 use. Administrative controls such as a control interlock that prevents locomotive power during fueling would also help during refueling, but breakaway devices are likely still needed for accident mitigation.

3.4.5 Materials

Almost all technologies have design rules around the optimal materials necessary to make the technology work and work safely; the same is true of hydrogen technology. The AAR documentation needs to be modified to include the design rules around the optimal materials necessary to make hydrogen technology (e.g., tanks, tubing, valves, fuel cells) work and work safely. Hydrogen will permeate into materials over time and can reduce the mechanical properties of materials. The degree to which their properties are degraded is a function of the temperature, hydrogen concentration, material, and stress state.

At room temperature, metals often used in hydrogen service are 316 or 316L stainless steel. These alloys have 10–14 percent Ni content and are thus expensive due to the cost of Ni. Hydrogen embrittlement is reduced at the temperatures and pressures of LH_2. Thus, the Ni content can be relaxed for material in contact with LH_2, such as 304 stainless steel, for which the Ni content can be as low as 8 percent. Other metals that are appropriate for hydrogen service are aluminum and copper, since these do not suffer hydrogen embrittlement. Any storage vessel design needs to account for hydrogen embrittlement; vessels do not necessarily have to be limited to these specific metals, if the tank design itself accounts for the embrittlement that may occur. ASME B31.12 specifies additional requirements for hydrogen tank design.

3.4.6 Physical Phenomena

Hydrogen is a very different fuel than diesel fuel in its physical properties. Diesel is a toxic liquid at room temperature, with heavier than air vapors that tend to sink when released. Hydrogen is a non-toxic gas at room temperature and is lighter than air, so it tends to rise when released. The vapors of diesel fuel and hydrogen ignite with different likelihood on exposure to ignition sources and are flammable over different ranges of fuel/air mixtures. Gaseous and liquid hydrogen are more similar to CNG and LNG, but even between hydrogen and natural gas, differences exist (Klebanoff, L. E., Pratt, J. W., & LaFleur, C. B., 2017). It is therefore important to be fully informed on the physical and combustion properties of hydrogen, compared to the incumbent diesel fuel and to the recently introduced (to rail) natural gas.

Although the AAR documents reference cryogenic liquids like LH_2, LN_2, LO_2, and argon, there is no discussion of low-temperature materials phenomena that can influence tank reliability and longevity. For example, some metals can undergo a ductile-to-brittle transition and for the 304 and 316 alloys, phases that are susceptible to this transition can be created by welding. There is a whole material science area devoted to this and significant ongoing work is being done.

The differing physical properties of hydrogen require some revision of the AAR documentation. Overall, the strategy for safe implementation set forth for NG/LNG should be directly applicable for establishing a fuel tender based on the use of GH_2 or LH_2, with some revision in the implementation details. For example, the purge requirements for LH_2 are different than LNG, because the colder LH_2 can liquefy and eventually freeze nitrogen. In addition, the temperatures at which some impact tests are conducted will be lower for LH_2. Volumetric tank sizes and flow rates will also be different, due to the different physical properties.

Interestingly, the research team found no mention in the AAR documents of stratification in LNG, nor the possibility of rollover arising from the compositional stratification where there can be a sudden burst of pressure during refueling or other mixing events. Regardless, it has no impact for hydrogen refueling considerations, because there is no stratification in LH_2 tanks due to the uniform composition of the LH_2 load.

4. Conclusion

From September 2018 to March 2021, in Livermore, CA, and Albuquerque, NM, Sandia National Laboratories studied the multiple ways to achieve low-emission train operation relative to current diesel technologies. These can include electrified track, battery electric locomotives, or hydrogen fuel cells. Different technologies may be more applicable to different types of rail applications (e.g., long-haul freight vs. regional passenger rail vs. switcher yards). Different technologies may fit differently based on multiple factors, such as economics, environmental impacts, safety hazards, and public acceptability. How well different technologies match up against different applications will inform how much of an impact the new technologies could make on a given application. The research team developed a method for quantifying these impacts, with an example given in Appendix A.

Hydrogen can provide many benefits to rail locomotive power operations, specifically offering interoperability, scalability, fast-refueling, and lightweight energy storage at scale. Hydrogen fuel cell powered locomotives can run on existing track, and so while new locomotives may be expensive, they avoid the need for expensive electrification of the track itself. A single hydrogen refueling facility could support multiple locomotives on multiple routes, making this technology scale much more effectively than electrified track that necessarily scales more linearly with each additional mile of track to be electrified. Hydrogen fuel cell locomotives can also benefit from fast refueling, especially compared to battery electric charging. Given the need for refueling infrastructure, hydrogen fuel cell powered locomotives would be most useful initially in applications that have limited geographic range; this could be a single rail route (with refueling on both ends), a switcher locomotive in a rail yard, a line-haul locomotive that does out-and-back trips, or a passenger train with a set route. Smaller and shorter applications will almost certainly use gaseous hydrogen storage onboard the locomotive, but longer and larger applications may need to use cryogenic liquid hydrogen. Currently, hydrogen is produced via steam methane reforming, so while emissions from the locomotive itself can be avoided, the more centralized hydrogen production would still produce emissions. However, hydrogen can be produced in a variety of ways, including on-site production, giving flexibility for hydrogen production and facility siting.

Several AAR MSRP standards were reviewed for hydrogen applicability. Some of the significant potential gaps in the current standards for use in hydrogen relate to the physical properties of hydrogen and how those properties can differ from diesel or natural gas fuels. Hydrogen is a flammable, non-toxic gas at room temperature that is lighter than air. Overall, the strategy for safe implementation set forth for NG/LNG should be directly applicable for establishing a fuel tender based on the use of GH_2 or LH_2, with some revision in the implementation details. For example, the purge requirements for LH_2 are different than LNG, because the colder LH_2 can liquefy and eventually freeze nitrogen. Volumetric tank sizes and flow rates will also be different, due to the different physical properties. Liquefied hydrogen is a cryogenic fluid that is much cooler than LNG. Finally, hydrogen can embrittle metal and so any storage vessel design needs to account for hydrogen embrittlement; vessels do not necessarily have to be limited to specific metals, if the tank design itself accounts for the embrittlement that may occur.

There are also gaps related to the rolling-stock car design (e.g., locomotive, tender, or tank cars) with the use of hydrogen. Ventilation is critically important for the safe use of a flammable gas such as hydrogen or natural gas, because ventilation dilutes the flammable gas to safe concentrations and removes the fuel/air mixture from the space. There is some ambiguity in whether spaces are passively vented or actively ventilated, and what concentration value is used for alarms and shutdowns (i.e., based on either the LFL or LEL). Furthermore, hydrogen fuel tanks are very different than diesel fuel tanks. Locating diesel tanks beneath the underframe of a locomotive is entirely reasonable and the underframe location has been successfully used for decades. Hydrogen tanks need to contain high-pressure gaseous hydrogen (up to 700 bar) or limit heat ingress into a very cold (20 K) supply of LH_2; additionally, if hydrogen leaks it will likely rise, making more beneficial for tanks to be near the top of rail cars. Finally, the vibration and shock experienced in the rail environment is significantly higher than other environments in which hydrogen fuel cells have typically been used (e.g., light-duty vehicles, stationary applications, etc.). This makes vibration testing of all aspects of hydrogen fuel cell technology critically important. If LH_2 is involved, then it is important that such testing be conducted at the cryogenic temperatures that the equipment will experience.

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Appendix A.
An Approach to Developing Impact Factors for Comparing Hydrogen Fuel Cell and Battery Technologies in Rail

When contemplating applying any new technology to an established application, it is useful to understand what the benefits are. Here the research team introduced the concept of relative "impact figures of merit" (IFMs) which indicate a benefit that a particular technology offers with regard to some aspect of performance. An example of this approach is given here for the greenhouse gas (GHG) and criteria pollutant (CP) emissions from a locomotive. The research team considered a switcher locomotive and determined the emissions (i.e., GHG, CP) from a switcher powered with different propulsion technology options. Then the research team developed relative IFMs that conveyed the environmental benefit or impact of these technologies.

To calculate emissions, the research team started with a mission profile, energy use profile, or duty cycle which specified how the technology is being used from an energy or power perspective. An example mission profile for a switcher locomotive is shown in Figure A.1.

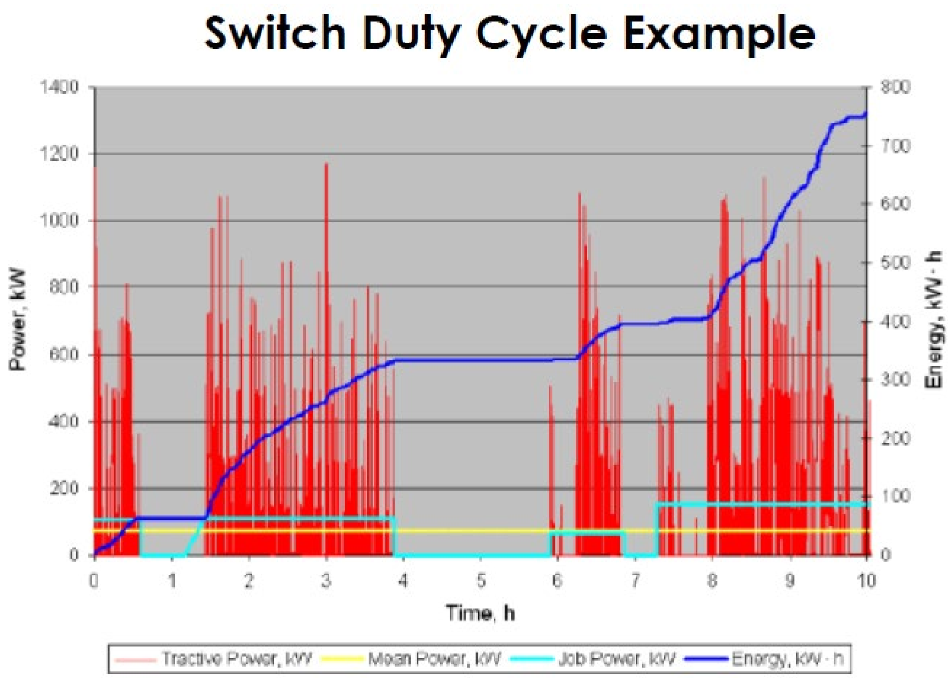

Figure A.1: Switch locomotive duty cycle
(Duty cycle courtesy of Andreas Hoffrichter)

Typically, each type of rail application (i.e., switcher, freight [or line haul], passenger) has a defining mission profile. In this example, the research team seeks to understand how the various technology options for powering a switch locomotive, assuming the duty cycle of Figure A.1, affect GHG and CP emissions, and to establish a numerical scoring on a 1 to 10 scale for each type of pollutant.

Given the duty cycle for a switch locomotive in Figure A.1, Figure A.2 outlines the initial approach.

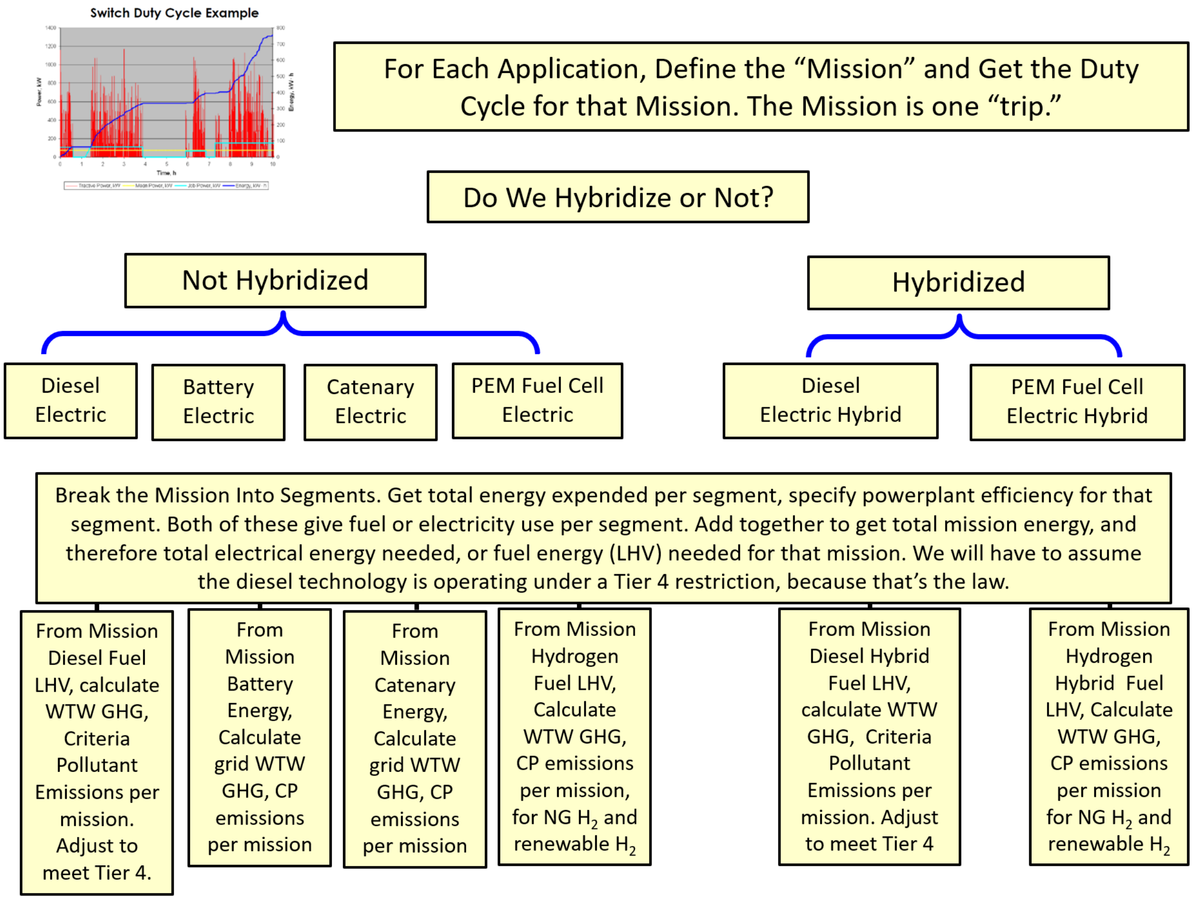

Figure A.2: Initial approach to developing environmental impact factors for different technology options for powering a switch locomotive with the duty cycle given by the plot

The first step is to define a "mission" based on the switcher duty cycle. That mission is most conveniently defined as "one trip" of some assumed distance. Alternatively, the mission could be operation for a segment of time, for example 10 hours. From the duty cycle, the research team may calculate the energy needed to perform that mission, which is ultimately the basis for the emissions calculations. The energy needed to perform the mission is the sum of the energies required to perform each step (or segment) of the total mission profile.

The next step is to identify the various propulsion technology options of interest. For this example, the research team imagined the switcher locomotive is powered by a Diesel Electric propulsion system, or alternatively a purely battery propulsion system driving the electric traction motors. Maybe the locomotive is powered by overhead electric lines ("Catenary Electric"), or perhaps by a hydrogen fuel cell providing electric power to the traction motors. These are examples of "Not Hybridized" technology options. It is, however, possible to combine technology options producing "Hybridized" propulsion systems.

Once the type of locomotive (e.g., switcher) is identified, the mission profile is acquired (Figure A.1), and the technology options identified, the research team calculated the emissions associated with the switcher profile, which is broken into segments. The profile can also be defined as the percent of time spent in various "notches" of the diesel engine, with the notches indicating partial load output. Ultimately, there is a need for the total energy expended per segment (or time spent in a “notch”). If the power plant efficiency is known at that level of load, then the fuel use can be calculated (e.g., diesel and hydrogen fuel cell) or the electricity used (e.g., battery and catenary) for that segment. Then the segment energy expenditures were added together to get the total mission energy, and therefore total fuel energy on a lower heating value (LHV) basis, or the electrical energy needed for that mission. There may be some external constraint on emissions, for example, it can be assumed that the diesel technology is operating under the U.S. Environmental Protection Agency (EPA) Tier 4 restrictions on CP. For the diesel numbers, even though the locomotive is constrained to Tier 4, the research team would have to account for the production and pathway emissions which add to the emissions from the locomotive beyond those “out of the tailpipe” which are regulated by the Tier 4 emission levels.

With the fuel use calculated (diesel engine and fuel cell) and the electrical energy needed (battery and catenary), emissions can be calculated using literature values for the “well to wheels” emissions associated with extracting, processing, and delivering and using a unit of LHV of diesel fuel, hydrogen fuel, or unit of grid energy for providing electricity to the train directly (catenary) or recharging an onboard battery (battery). Sources used in past studies included estimates for GHG emissions from the European Union (Edwards, R., Larive, J. -F., Mahieu, V., & Rouveirolles, P., March 2007) (Edwards, R. Larive, J. -F., Rickeard, D., & Weindorf, W., July 2013), as well as CP emissions from a State of California study (Stoner, S., Olson, T., Addy, M., Tuvell, R., Shapiro, R., & Blevins, B. B., February 2007). Other sources can be used, for example, using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model from Argonne National Laboratory (Wang, M., August 1999). Greenhouse Gas emissions are usually expressed as CO_2 (eq.), where the (eq.) indicates consideration of not only CO_2 itself, but other important GHGs such as N_2O and CH_4. The total of these three species are summed together in the CO_2 (eq.) notation. Criteria pollutants of importance are oxides of nitrogen (NO_x), hydrocarbons (HC) and particulate matter (PM). Since emissions depend on how electricity is produced, or how hydrogen is made, there needs to be specification of what type of electricity or hydrogen is being used. Examples for how this calculation is performed for a high-speed ferry or a coastal research vessel have been published recently (Klebanoff, L. E., Pratt, J. W., & LaFleur, C. B., 2017) (Madsen, R. T., Klebanoff, L. E., Caughlan, S. A. M., Pratt, J. W., Leach, T. S., Applegate Jr., T. B., Kelety, S. Z., Wintervoll, T. - H., Haugom, G. P., Teo, A. T. Y., & Ghosh, S., September 2020).

Using fake (i.e., made up) data for the purposes of explanation, the estimates for emissions may look like that shown in Table A.1.

Table A.1: Fake data “per mission” emissions for a switcher locomotive using various technology options for the propulsion.

Species	Diesel Tier 4 kg/mission	Battery, kg/miss.	Catenary, kg/miss.	Fuel Cell, NG H_2 kg/miss.	Fuel Cell, Ren H2 kg/miss.	Diesel Hybrid Tier 4 kg/miss.	Fuel Cell Hybrid, NG H2 kg/miss.	Fuel Cell Hybrid, Ren. H2 kg/miss.
CO_2(eq).	90	56	50	88	3	83	45	2
NO_x	56	38	34	47	1	50	443	.5
HC	3300	2200	1900	3800	100	2800	3100	50
PM	1.5	0.8	0.6	1.2	1.0	1.2	1.1	0.05

At this point, "per mission" emissions of CO_2 (eq.), NO_x, HC and PM for the various technology options is available. How does the research team convert those to IFMs in such a way that the information contained in the relative emissions is maintained, but end up with a number from 1–10 that can be compared with other impact figures of merit for other aspects (e.g., safety)? This is the basic motivation for using an IFM, that relative IFMs can be combined for different attributes (e.g., safety, emissions, cost, etc.) to produce a total impact figure of merit that allows comparisons between technologies, widely viewed across attributes, with a single number.

Starting from the fake data in Table A.1, first it is assumed that all pollutant species matter equally. For each pollutant species (i.e., for each row in Table A.1), the research team identifies the largest number. Then, divide this largest number by the other emission values for each technology. This allows us to get a large number associated with a large benefit (or impact). By this mathematical manipulation, for the row for CO_2 (eq.), the research team would have revised entries of: 90/90; 90/56; 90/50; 90/88; 90/3; 90/83; 90/45; 90/2 as shown in Table A.2.

Table A.2: Fake data "per mission" emissions for a switcher locomotive using various technology options for the propulsion, manipulated as described in the text to produce IFMs

Species	Diesel Tier 4 kg/mission	Battery, kg/miss.	Catenary, kg/miss.	Fuel Cell, NG H_2 kg/miss.	Fuel Cell, Ren H2 kg/miss.	Diesel Hybrid Tier 4 kg/miss.	Fuel Cell Hybrid, NG H2 kg/miss.	Fuel Cell Hybrid, Ren. H2 kg/miss.
CO_2(eq).	1	1.61	1.8	1.02	30	1.08	2.0	45

So, for a particular application (switcher), for a particular pollutant species (CO_2), the Fuel Cell Hybrid Ren. H_2 is 45 times better than Diesel Tier 4 for CO_2 emissions. At this point, this is a relative scale of impact, but not on the desired 0–10 scale.

Now, the impact factors were put on a 0–10 scale, while preserving the relative impacts amongst the different propulsion technologies: take each number, divide by the largest number in the row (most benefit), then multiply by 10. So, starting with the entries in Table A.2:

For Diesel Tier 4, take: 1/45 = 0.0222, multiplying by 10 = 0.222

For Battery, take: 1.61/45 = 0.0357, multiplying by 10 = 0.357

For Fuel Cell Renewable H_2, take: 30/45 = 0.666, multiplying by 10 = 6.66

For Fuel Cell Hybrid Renewable H_2, take: 45/45 = 1.0, multiplying by 10 = 10

These manipulations take the IFMs from Table A.2 and produce IFMs on the desired –10 scale, as presented in Table A.3.

Table A.3: Fake data "per mission" emissions for a switcher locomotive using various technology options for the propulsion, manipulated as described in the text to produce IFMs on a 0–10 scale for CO_2 (eq.)

Species	Diesel Tier 4 kg/mission	Battery, kg/miss.	Catenary, kg/miss.	Fuel Cell, NG H_2 kg/miss.	Fuel Cell, Ren H2 kg/miss.	Diesel Hybrid Tier 4 kg/miss.	Fuel Cell Hybrid, NG H2 kg/miss.	Fuel Cell Hybrid, Ren. H2 kg/miss.
CO_2(eq).	0.222	0.357	0.40	0.226	6.66	0.24	0.44	10.0

Now there is a common scale of 0–10, while at the same time preserving that the Fuel Cell Hybrid Ren. H_2 is 45 times better than Diesel Tier 4 in this CO_2 category (10/0.222 = 45.0).

To consider the other pollutants, the research team assumes that all pollutant species matter equally (have the same intrinsic level of impact), and that the IFMs are additive. Performing the same manipulations for the other pollutants shown in Table A.1, then Table A.4.

Table A.4: Fake data "per mission" emissions for a switcher locomotive using various technology options for the propulsion, manipulated as described in the text to produce IFMs on a 0–10 scale for all the pollutants (GHG, CP) under consideration

Species	Diesel Tier 4 kg/mission	Battery, kg/miss.	Catenary, kg/miss.	Fuel Cell, NG H_2 kg/miss.	Fuel Cell, Ren H2 kg/miss.	Diesel Hybrid Tier 4 kg/miss.	Fuel Cell Hybrid, NG H2 kg/miss.	Fuel Cell Hybrid, Ren. H2 kg/miss.
CO_2(eq).	0.222	0.357	0.40	0.226	6.66	0.240	0.444	10
NO_x	0.089	0.131	0.147	0.106	5.0	0.100	0.0112	10
HC	0.151	0.227	0.263	0.131	5.0	0.178	0.161	10
PM	0.333	0.623	0.833	0.416	0.5	0.416	0.453	10

The Total Emissions Impact Figure of Merit (TEIFM) for each technology, for the given application, is then the sum of the individual IFMs, then divided by 4 to get a result normalized to 10. This is shown in Table A.5.

Table A.5: Fake data "per mission" emissions for a switcher locomotive using various technology options for the propulsion, manipulated as described in the text to produce IFMs on a 0–10 scale for all the pollutants (GHG, CP) under consideration. The TEIFM for each technology is the sum of the IFMs for the individual pollutants (GHG, CP)

Species	Diesel Tier 4 kg/mission	Battery, kg/miss.	Catenary, kg/miss.	Fuel Cell, NG H_2 kg/miss.	Fuel Cell, Ren H2 kg/miss.	Diesel Hybrid Tier 4 kg/miss.	Fuel Cell Hybrid, NG H2 kg/miss.	Fuel Cell Hybrid, Ren. H2 kg/miss.
CO_2(eq).	0.222	0.357	0.40	0.226	6.66	0.240	0.444	10
NO_x	0.089	0.131	0.147	0.106	5.0	0.100	0.0112	10
HC	0.151	0.227	0.263	0.131	5.0	0.178	0.161	10
PM	0.333	0.623	0.833	0.416	0.5	0.416	0.453	10
Total Emiss. Impact Factor (TEIF)	**0.198**	**0.334**	**0.410**	**0.219**	**4.29**	**0.233**	**0.267**	**10**

From this "fake example," the TEIFM for fuel cell running on renewable H_2 is 4.29/0.198 = 21.66 times better than Diesel Tier 4 considering all the pollutant emissions. Repeating, this is a fake result based on fake data, shown here to describe the approach to generating IFMs.

Each TEIF factor is for one locomotive, characterized by a particular duty cycle (e.g., switcher), for one type of technology (e.g., battery). So the TEIFs need to be indexed: TEIFM (x,y) where x is the type of application/duty cycle (e.g., line haul, passenger, and switcher), and y is the type of technology (e.g., battery, catenary, and fuel cell). The IFMs do not contain the number of locomotives, which would have to be accounted for elsewhere.

This formalism of using IFMs can be developed for other aspects of locomotive operation. In addition to emissions, there is safety, capital cost and O&M cost aspects that can be considered. These aspects can have developed for them a set of total impact factors (e.g., TCIF for cost), all on the same 0–10 scale as demonstrated for the emissions, which can then all be added together, and even weighted if desired (e.g., safety 2 times as important as emissions), to get the overall TIF for the technology.

To see a real (as opposed to fake) example, a presentation for the H2@Rail Workshop gives calculation results for several propulsion power systems for the Switch, Line Haul and Passenger Rail applications (Ehrhart, B., Klebanoff, L., Hecht, E. Headley, A., Ng, M., & Markt, C., March 2019).

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ACH	Air Changes per Hour
Al	Aluminum
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
AAR	Association of American Railroads
AHJ	Authority Having Jurisdiction
BPVC	Boiler and Pressure Vessel Code
BNSF	Burlington Northern Santa Fe Railway
CN	Canadian National Railway
CP	Canadian Pacific Railway
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
CP	Criteria Pollutant
FRA	Federal Railroad Administration
FTM	Fuel Tank Monitor
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
HEX	Heat Exchanger
HP	High-pressure
HC	Hydrocarbon
H_2	Hydrogen
ITP	Independent Third Party
IFM	Impact Figures of Merit
ISO	International Organization for Standardization
KCS	Kansas City Southern Railway
LHV	Lower Heating Value
LH_2	Liquid Hydrogen

ACRONYMS	EXPLANATION
LNG	Liquid Natural Gas
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
LEL	Lower Explosion Limit
LFL	Lower Flammability Limit
MSRP	Manual of Standards and Recommended Practices
MAOP	Maximum Allowable Operating Pressure
MAWP	Maximum Allowable Working Pressure
CH_4	Methane
NASA	National Aeronautics and Space Administration
NACE	National Association of Corrosion Engineers
NFPA	National Fire Protection Association
NG	Natural Gas
Ni	Nickel
N_2	Nitrogen
NOx	Nitrogen Oxide
NS	Norfolk Southern
NER	Normal Evaporate Rate
PM	Particulate Matter
PRD	Pressure Relief Device
PEM	Proton Exchange Membrane
TCS	Tank Connection Space
TPRD	Temperature-activated Pressure Relief Device
TOR	Top of Rail
TEIFM	Total Emissions Impact Figure of Merit
TC	Transport Canada
TTCI	Transportation Technology Center
UP	Union Pacific Railway
UFL	Upper Flammable Limit
DOT	U.S. Department of Transportation
EPA	U.S. Environment Protection Agency

ACRONYMS	EXPLANATION
USPHS	U.S. Public Health Service