Final Technical Report

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Golden Field Office
Hydrogen, Fuel Cells, and Infrastructure Technologies Program

Grant Award No: DE-FG36-05GO85049

Fuelcell Prototype Locomotive

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Nuvera Fuel Cells Inc, Cambridge, MA
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Regional Transportation District – Denver, CO
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Executive Summary

An international industry-government consortium is developing a fuelcell hybrid switcher locomotive for commercial railway applications and power-to-grid generation applications. The current phase of this on-going project addresses the practicalities of on-board hydrogen storage, fuelcell technology, and hybridity, all with an emphasis on commercially available products.

Through practical evaluation using designs from Vehicle Projects' Fuelcell-Powered Underground Mine Loader Project, the configuration of the fuelcell switcher locomotive changed from using metal-hydride hydrogen storage and a pure fuelcell power plant to using compressed hydrogen storage, a fuelcell-battery hybrid power plant, and fuelcell stack modules from Ballard Power Systems that have been extensively used in the Citaro bus program in Europe.

The new overall design will now use a RailPower battery hybrid Green Goat™ as the locomotive platform. Keeping the existing lead-acid batteries, we will replace the 205 kW diesel gen-set with 225 kW of net fuelcell power, remove the diesel fuel tank, and place 14 compressed hydrogen cylinders, capable of storing 70 kg of hydrogen at 350 bar, on the roof. A detailed design with associated CAD models will allow a complete build of the fuelcell-battery hybrid switcher locomotive in the next funded phase.

1.0 Introduction

An international industry-government consortium is developing a fuelcell hybrid switcher locomotive for commercial railway applications and power-to-grid generation applications. The current phase of this on-going project addresses the practicalities of on-board hydrogen storage, fuelcell technology, and hybridity, all with an emphasis on commercially available products.

The Fuelcell-Powered Underground Mine Loader Vehicle (Fig. 1; DOE Project DE-FC36-01GO11095) is a battery hybrid that incorporates metal-hydride hydrogen storage and PEM fuelcells. Using this as a design basis for industrial type vehicles, we tested and analyzed various subsystems for incorporation into the switcher locomotive. Consideration was also given to existing fuelcell-powered busses to use existing technology where feasible to reduce costs and increase safety and reliability.

Fig.1. Diesel base vehicle (left); fuelcell powerplant installed (right)

Several design and integration challenges arise, such as weight, center of gravity, packaging, and safety, when implementing such a large hydrogen fuelcell vehicle. Harsh operating conditions, especially shock loads during coupling to railcars, require component mounting systems capable of absorbing high energy. Additionally, system design must address railway-industry regulations governing safety and such events as derailment, side impact from yard traffic, refueling, and maintenance.

2.0 Approach

Previous conceptual work on the fuelcell switcher locomotive resulted in a preliminary design of 1.2 MW of gross fuelcell power coupled with 250 kg of hydrogen stored in metal-hydride. The 1.2 MW consisted of eight (8) 150 kW gross power modules in electrical parallel resulting in 600 VDC at 2,000 amps. The metal-hydride has a practical system weight % of approximately 0.7 resulting in a total hydrogen storage weight of 36,000 kg (79,000 lbs), which fits into a GP9 locomotive platform, with an established weight of 109 metric tons (240,000 lbs).

With the conceptual design established, we designed and built a 150 kW gross power fuelcell module to be used as a building block for the 1.2 MW gross powerplant. Nuvera Fuel Cells Inc. was tasked with this design based on their PEM Forza™ Cathodic Water Injection (CWI), 18.7 kW gross fuelcell stacks. Funding for this effort was provided by the Railway Technical Research Institute (RTRI), Tokyo, Japan. Once the power module was built, RTRI installed it into a train test bed and tested the module under real-world conditions.

Hydrogen storage is always a major concern for any vehicle design. Metal-hydride offers a degree of safety and can be designed for low pressure use, but is heavy, expensive, and no large-scale systems are offered. In fact, the fuelcell-powered mine loader's 14 kg of stored hydrogen is one of the largest hydrogen systems for vehicles ever built. On the other hand, compressed hydrogen at 350 bar (5,000 psi) is used extensively in fuelcell bus designs and is commercially available. Liquid fuels, such as methanol, require reformers that are still quite large for practical large vehicle use. Validation of the fuelcell-powered mine loader metal-hydride storage system will contribute to choosing the type of hydrogen storage system that will be the most practical.

Another key factor is determining whether the powerplant should be a pure fuelcell or a fuelcell-hybrid design. Design considerations, such as the duty cycle of the vehicle, must be weighed against the economics of the overall system. Validation of the fuelcell-powered mine loader fuelcell-battery hybrid design will result in a final decision of the degree of hybridity, if any.

3.0 Results

3.1 Fuelcell Power Module

The 150 kW gross power fuelcell module (Fig. 2) was built and delivered to RTRI for testing in Tokyo in February, 2006. The power module has dimensions of 1650 mm (L) x 1250 mm (W) x 1500 mm (H) and weighs 1650 kg (3,600 lbs). The module consists of eight PEM fuelcell stacks with each stack having 116 cells. This results in 250 amps and 75 VDC at full load per stack. When all eight stacks are connected in electrical series, the resulting gross power is 150 kW or 250 amps and 600 VDC full load.

Fig. 2. Back and side of 150 kW module showing the eight fuelcell stacks.

The power module includes a unique design wherein purged hydrogen is reused, resulting in hydrogen usage of 99.95%. The system also includes a closed loop water system that requires no additional water. Since the fuelcell stacks are CWI, there is no need for humidification of cathodic air. Previous designs have included a cathode charge air cooler, which has been eliminated in this version. An on-board water de-ionizer ensures that the conductivity of the water remains at acceptable levels.

Fig. 3. 150 kW module installed in RTRI commuter train for testing.

The factory acceptance test consisted of running the power module more than 8 hours at full power. The actual output power level was 138.7 kW gross, 122.9 kW net; resultant power levels equate to parasitic losses of 15.8 kW or 11.4%. The acceptance test also demonstrated the ability of the power module to operate at 150 kW gross power resulting in a net output of 128 kW. At the slightly higher output power, the parasitic losses increased to 22 kW or 14.7%.

Upon delivery of the power module to RTRI, it was installed into a new train car test bed (Fig. 3). For purposes of convenience, compressed gaseous hydrogen was used. The power module and train car were instrumented and tested on an outside test track as well as in a rolling stock test facility. Unfortunately, results of the testing were not favorable; at different times, multiple fuelcell stack modules failed. The resulting analysis indicated excessive water on the anode side, which flooded the cells. The cause of this flooding was the hydrogen purging scheme, as well as the design's inability to handle long idling times. The Forza™ stacks are based on a Nuvera stationary design, which became a fatal flaw.

3.2 Metal-Hydride Evaluation

The fuelcell-powered mine loader uses two metal-hydride storage units in a saddlebag configuration with each module capable of storing 7 kg of hydrogen (Fig. 4). The metal-hydride is a C15 alloy made up of Manganese (25-50%), Vanadium (10-25%), Titanium (15-35%), and Zirconium (2.5-10%). Keeping within the design requirements of operating the metal-hydride at no more than 14 bar (200 psia) and 45 C, the measured hydrogen capacity of the alloy was 1.46 weight %. Another design requirement was a fast refill time of less than 30 minutes; since the rate of fill is a function of heat removal, the design of

Fig. 4. One metal-hydride module with mounting guides.

the metal-hydride system was driven by this requirement.

Each metal-hydride module (two total) consists of two smaller modules each with 276, 5/8 inch OD inconel tubes, manifolded together, housed in stainless steel water enclosures (Fig. 5). This results in over 1,100 tubes which lead to a 0.7 system weight %. However, this also allows a fast fill of less than 15 minutes, a remarkable achievement.

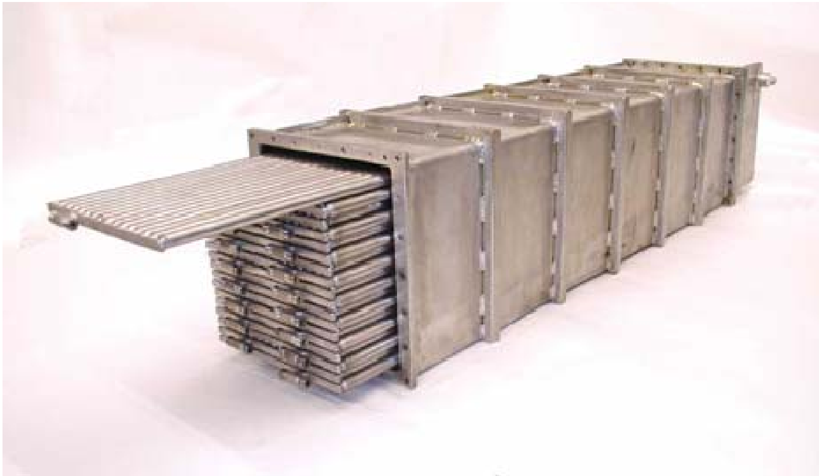

Fig. 5. One of four water jacket enclosures; two of these make up one module.

The system cost due to the complexity of the design is quite high. By incorporating a larger quantity for the locomotive the projected cost is still approximately $10,000 per kg of hydrogen. This alone prohibits the use of metal-hydride on a large scale basis. Weight also does become a factor, especially if the locomotive is a battery hybrid. Finally, there has not been any large-scale engineering and manufacturing of metal-hydride systems to acknowledge this technology as commercially feasible for large vehicle applications.

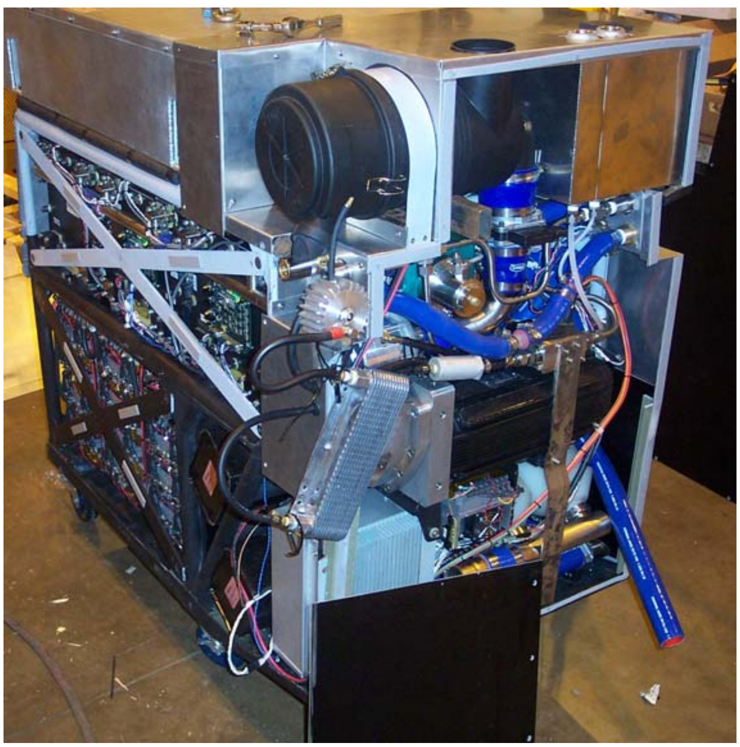

Fig. 6. Loader power module with fuelcell stacks behind upper frame cross members, batteries behind lower frame cross members.

3.3 Fuelcell-Battery Hybrid Evaluation

The fuelcell-powered mine loader is a fuelcell-battery hybrid design. Coupled to 90 kW of fuelcell gross power is a 12 kWh Nickel-Metal-Hydride (NiMH) battery capable of providing an additional 60–70 kW of power for 5–10 minutes (Fig. 6). Because of the power peaks required during certain operations of the loader, such as loading the bucket with ore and driving up ramps, a battery hybrid design is practical. This design minimizes the use of fuelcells, and thus reduces the cost of the system, allowing the fuelcell to operate in a more steady state mode, which prolongs the life of the fuelcell.

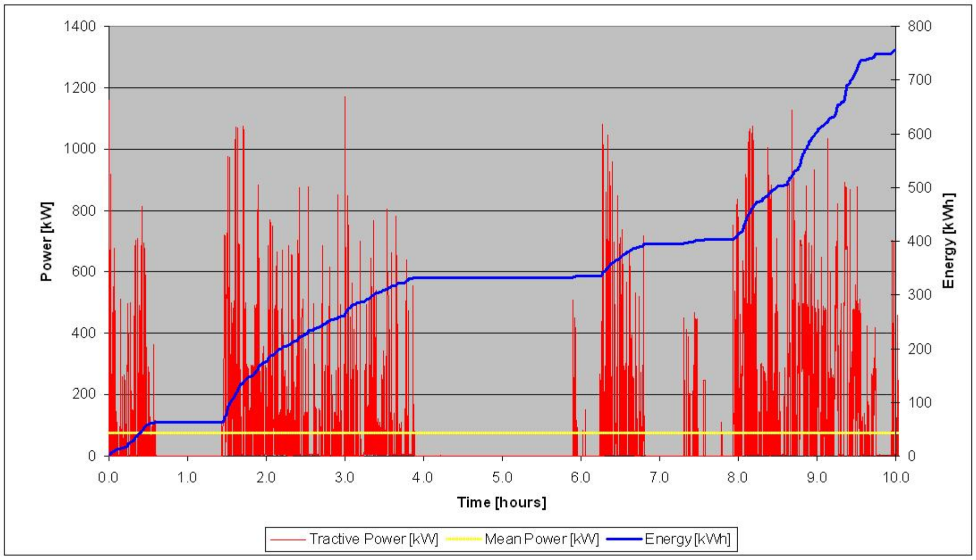

Fig. 7. Duty cycle of a typical switcher locomotive.

In general, a battery-hybrid design is not practical for rail applications. The acceleration of a train is limited by the available adhesion between the wheel and the rail, and not by the available power. Typically, full traction power is not used until the train speed has reached 15-25 km/h (10-15 mph). Since the switcher locomotive is a captive vehicle, not traveling outside a switcher yard, its top speed generally remains below 15 km/h (10 mph). However, because the duty cycle of a switcher locomotive has many power peaks (Fig. 7) due to initial acceleration pushing train cars, there is an advantage in using a battery hybrid to reduce overall system costs. Cost models have shown that there is an optimum cost tradeoff between having a 100% fuelcell powerplant and a 100% lead-acid battery powerplant [1]. With the switcher locomotive designated at 1.2 MW, having a fuelcell-battery hybrid with 400 kW of fuelcell power is the most cost effective design.

Fig. 8. BNSF battery-hybrid switcher locomotive platform.

A commercially available battery-diesel hybrid switcher locomotive has been developed by RailPower Corp (Fig. 8). Utilizing older locomotive core platforms, RailPower refurbishes the trucks and traction motors, cab, and wiring, and installs a large lead-acid battery and a small diesel genset. Claiming 2 MW of available power, the Green Goat™ is a first attempt at providing an alternative power source for large rail vehicles. The lead-acid battery was chosen based on economics. Because the battery is lead-acid, it must be oversized to compensate for the small depth of discharge that is used to prolong the life of the battery. A typical depth of discharge for a lead-acid battery is about 20%. On the fuelcell-powered mine loader, the NiMH battery uses a typical depth of discharge of 70-80%, resulting in greater energy density than the lead-acid battery.

3.4 Hazard Analysis Report

Washington Safety Management Solutions (WSMS) has worked with Vehicle Projects LLC performing Hazard Analysis (HA) reports for many years. In fact, their completed HA report on the fuelcell mine locomotive has been accepted by DOE as a template on how to conduct a HA for new solicitations.

A major design change was incorporated in the project that addressed the hydrogen storage issue. As previously discussed, metal-hydride storage, besides being costly and heavy, has not been designed on a large scale for any type of industrial vehicle. To our knowledge, the largest resides on the fuelcell underground mine loader, which is capable of storing 14 kg of hydrogen. Based on this design, WSMS compared metal-hydride storage to compressed hydrogen cylinders that are mounted underneath the platform where the diesel fuel tank sits and on top of the battery rack.

A thorough safety analysis highlighted two factors that led to the packaging of the hydrogen system above the battery pack. First, because of the buoyancy of hydrogen, storing hydrogen below void volumes in the locomotive platform, battery rack, and rear hood could lead to confinement of leaked hydrogen and increase the possibility of detonation. In contrast, roof-line storage allows for harmless upward dissipation of hydrogen in the event of a leak. Second, locating the hydrogen tanks on the roof minimizes the likelihood of damage from common events such as derailment, track debris, and impact from yard traffic, such as fueling trucks. Because of the relatively light weight of the hydrogen storage tanks (about 100 kg each), the roof location has minimal effect on the vehicle’s center of gravity. Indeed, after conversion to hydrogen fuelcell power, a ballast of approximately 9,000 kg will be placed in the undercarriage to bring the locomotive weight to its specified value of 127 metric tons. Locomotives have a specified weight to support required tractive effort, which is limited by wheel adhesion.

3.5 CAD Model

Vehicle Projects LLC completed a comprehensive CAD model of the final configuration for the fuelcell switcher locomotive. The original fuelcell power plant was based on the Nuvera 150 kW design, but due to many problems – the power plant was overweight, too large, had an inadequate purging scheme, and was costly – the project team decided to incorporate a power module from Ballard Power Systems. Based on their successful Citaro bus program in Europe, Ballard has established a 150 kW gross power fuelcell module that incorporates hydrogen purging, air humidification, water management, and cell voltage monitoring. The P5 module is a proven design with over 1.5 million km of use in busses.

As previously noted, the hydrogen storage will use Dynetek 350 bar (5,000 psi) composite wrapped cylinders, which are the same type of cylinders used on the Citaro bus program. Both the Ballard power module and the Dynetek cylinders are commercially available products.

The CAD schematic in Fig. 9 shows the various components and voltage busses the fuelcell switcher locomotive will implement. A DC/DC converter will supply 250 kW net fuelcell power to charge the batteries and power the traction motors. 70 kg of compressed hydrogen will supply enough fuel for approximately 8-10 hours of operation. Cooling of the fuelcell stacks and components is provided through two, 2-pass cross counter flow radiators attached to the roof. All fuelcell balance-of-plant is controlled through a central National Instruments Compact RIO controller.

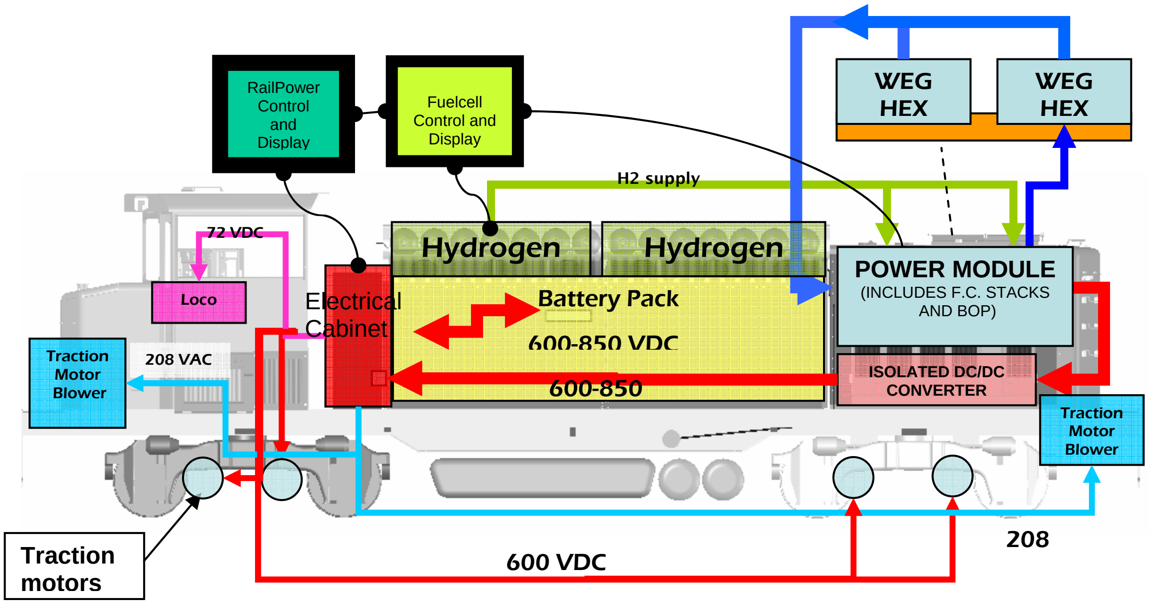

Fig. 9. System layout of the fuelcell hybrid locomotive including 225 kW net fuelcell power module, DC/DC converter, hydrogen storage, and control interface.

The fuelcell power plant, power converter, and cooling module are housed in the rear compartment of the locomotive. Already housed in the rear compartment are the locomotive air compressor, which is used for brakes and various other locomotive systems, and a blower motor that provides cooling to the rear traction motors located on the locomotive trucks. These two components occupy the lower left side of the rear compartment and were not modified in order to minimize redesign of the existing locomotive systems. Service points of the power plant system greatly influenced the overall component layout in the rear compartment (Fig. 10 illustrates the service points). Each of these service and access points – de-ionized water fill and filter, electrical panels, DC/DC converter panel, batteries, and resin filter – can be accessed from the outer platform of the locomotive. Longer service-interval components, such as air pre-filter, air compressor belt, and air system lubricant, can be accessed from within the rear compartment. All service points are located on the perimeter of the fuel cell power plant to allow full service without module removal. As shown in Fig. 11, the power plant is situated on the right side of the rear compartment. Because the power converter requires minimal access, it is located below the power plant; this enabled the fuel cell stack modules to be oriented symmetrically opposite on

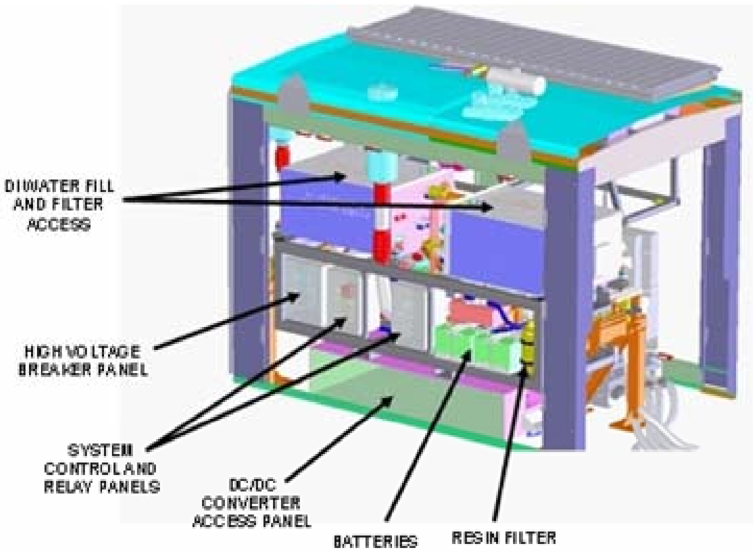

Fig. 10. Exterior accessible service points. The system was packaged to allow for maintenance and service access while on board the locomotive.

the same plane, thus allowing access to the stack module top covers or removal of only the stack modules. This layout also permits symmetric piping of air and coolant to both fuel cell stack modules, resulting in closely balanced flow for the air and coolant systems, which are driven by a single compressor and pump, respectively.

The overall fuelcell switcher locomotive layout is shown in Fig. 12. Isolation mounting of all fuel cell system modules to the locomotive is of critical importance. Because switcher locomotives are used to move other cars in rail yards, they are constantly coupling to other cars, which can lead to shock loads up to 10 Gs. Although they are of short duration, shocks of this magnitude could lead to immediate or fatigued failure of components or mounting structures. To mitigate this harsh environment, each module is isolated from the impact loads through the use of springs, specifically rubber or synthetic mounts or isolators. The isolation system also provides proper shock protection in the horizontal, lateral, and vertical directions.

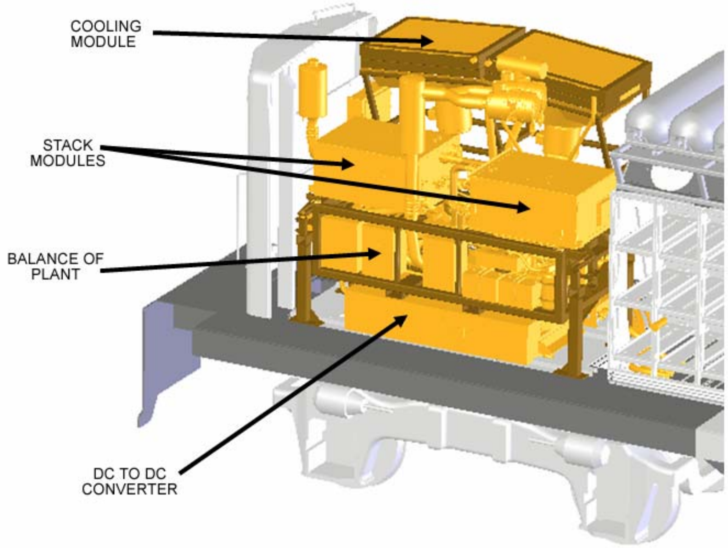

Fig. 11. Rear compartment layout. Systems were designed as bolt in modules, requiring minimal modifications to the locomotive platform. This allows for off line fabrication and testing of modules prior to vehicle installation.

4.0 Conclusions and Discussion

During the current phase of this multi-phase project, we developed and built a 150 kW prototype power module. Based on a previous design, Nuvera Fuel Cells integrated their Cathodic Water Injection (CWI) Forza™ fuelcell stacks into a module that was installed into a test train and evaluated.

Testing of the 150 kW module resulted in multiple fuelcell stack failures, and an inadequate purging scheme did not manage water on the anode side, which caused flooding of the membranes. The end design also resulted in the prototype module being overweight, excessively large, and too costly. These are obviously important factors for acceptance by end users.

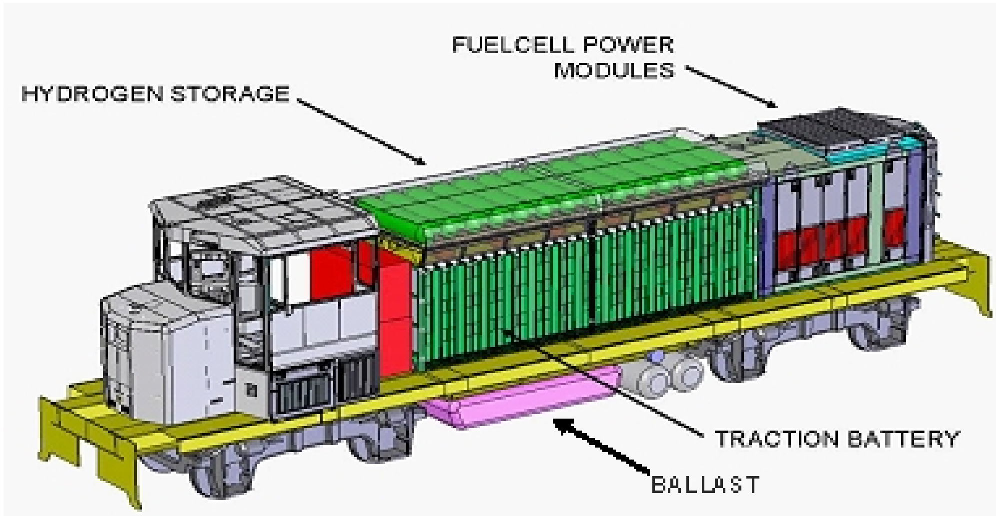

Fig. 12. Compressed hydrogen is stored in fourteen cylinders above the traction battery. The ballast will replace the diesel fuel tank to maintain tractive effort and center of gravity.

Work was completed on a fast-fill metal-hydride storage system capable of storing 14 kg of hydrogen. This system will be used in a mine loader for evaluation; however, the resulting design does not appear scalable for larger systems such as the locomotive. The fast fill of the system adds tremendous complexity to the system and thereby, cost. Reliability is also questionable due to the high parts count.

Based on the above results, we changed our design methodology to incorporate more proven fuelcell and hydrogen storage technology. We also changed the base platform from a pure fuelcell locomotive to a fuelcell-battery hybrid locomotive in order to reduce capital costs. Our design is now based on Ballard Power Systems' Mark 902 P5, 150 kW PEM gross power fuelcell modules used on the Citaro bus program in Europe. These modules have over 1.5 million km of proven reliability over three years. We also decided to incorporate Dynetek's 350 bar composite cylinders also used on the Citaro bus program. Though metal hydride was initially chosen, the cost to develop a system capable of storing at least 70 kg of hydrogen was too great and no designs of this magnitude exist.

The new overall design will now use a RailPower battery hybrid Green Goat™ as the locomotive platform. Keeping the existing lead-acid batteries, we will replace the 205 kW diesel gen-set with 225 kW of net fuelcell power, remove the diesel fuel tank, and place 14 compressed hydrogen cylinders, capable of storing 70 kg of hydrogen at 350 bar, on the roof.

References

[1] A.R. Miller, Least-Cost Hybridity Analysis of Industrial Vehicles. European Fuel Cell News, Vol. 7, January 2001, pp. 15-17.

Technology Transfer Activities

"System Design of a Large Fuelcell Hybrid Locomotive," ASME Fifth International Fuel Cell Science, Engineering & Technology Conference, New York City, New York, 18-20 June 2007

"Fuelcell Locomotives for Seaports and Power-to-Grid Applications," Second European Ele-Drive Transportation Conference (EET 2007), Brussels, Belgium, 30 May-1 June 2007

"Fuelcell Hybrid Switcher Locomotive for Seaports," Hydrogen and Fuel Cells 2007, Vancouver, British Columbia, 29 April-2 May 2007

"Fuelcell Hybrid Switcher Locomotive," Locomotive Maintenance Officer's Association Meeting, Omaha, Nebraska, 22-23 March 2007

"Comparison of Practical Hydrogen-Storage Volumetric Densities," NHA Annual Hydrogen Conference, San Antonio, Texas, 19-22 March 2007

"Fuelcell Locomotives for Urban Rail Applications," Faster Freight Cleaner Air, Long Beach, California, 26-28 February 2007

"Variable Hybridity Fuelcell Locomotive," H_2Expo International Conference and Trade Fair on Hydrogen and Fuel Cell Technologies, Hamburg, Germany, 25-26 October 2006

"Ammonia Fuel for Rail Transportation," Ammonia Conference 2006, Denver, CO, 9-10 October 2006

"Variable Hybridity Fuelcell-Battery Switcher," Locomotive Maintenance Officer's Association Meeting, Chicago, IL, 17-20 September 2006

"Technical Issues in Development of a Variable Hybridity Fuelcell Locomotive," Hydrogen Train and Hydrail Conference, Herning, Denmark, 6-7 June 2006

"Fuelcell Hybrid Locomotives: Applications and Benefits," Joint Rail Conference 2006, Atlanta, GA, 4-6 April 2006

"Variable Hybridity Fuelcell-Battery Road-Switcher," Locomotive Maintenance Officer's Association Meeting, Greenville, SC, 9 March 2006

"Fuelcell Hybrid Locomotives for Urban Switchyards," Faster Freight, Cleaner Air 2006, Long Beach, CA, 30 January – 1 February 2006

“Analysis of Fuelcell Hybrid Locomotives,” Ninth Grove Fuel Cell Symposium, London, England, 3-6 October 2005

“Fuelcell Locomotives,” Locomotive Maintenance Officer’s Association Meeting, Chicago, IL, 18-20 September 2005

“Technical Challenges of Large Fuelcell Vehicles,” European Fuel Cell Forum, Lucerne, Switzerland, 4-8 July 2005.

Washington Group International

Integrated Engineering, Construction, and Management Solutions

Preliminary Safety Analysis – Hazard Identification & Evaluation

Vehicle Projects – Defense Fuelcell Locomotive Project – Phase 3

Fort Worth, TX; December 1, 2006

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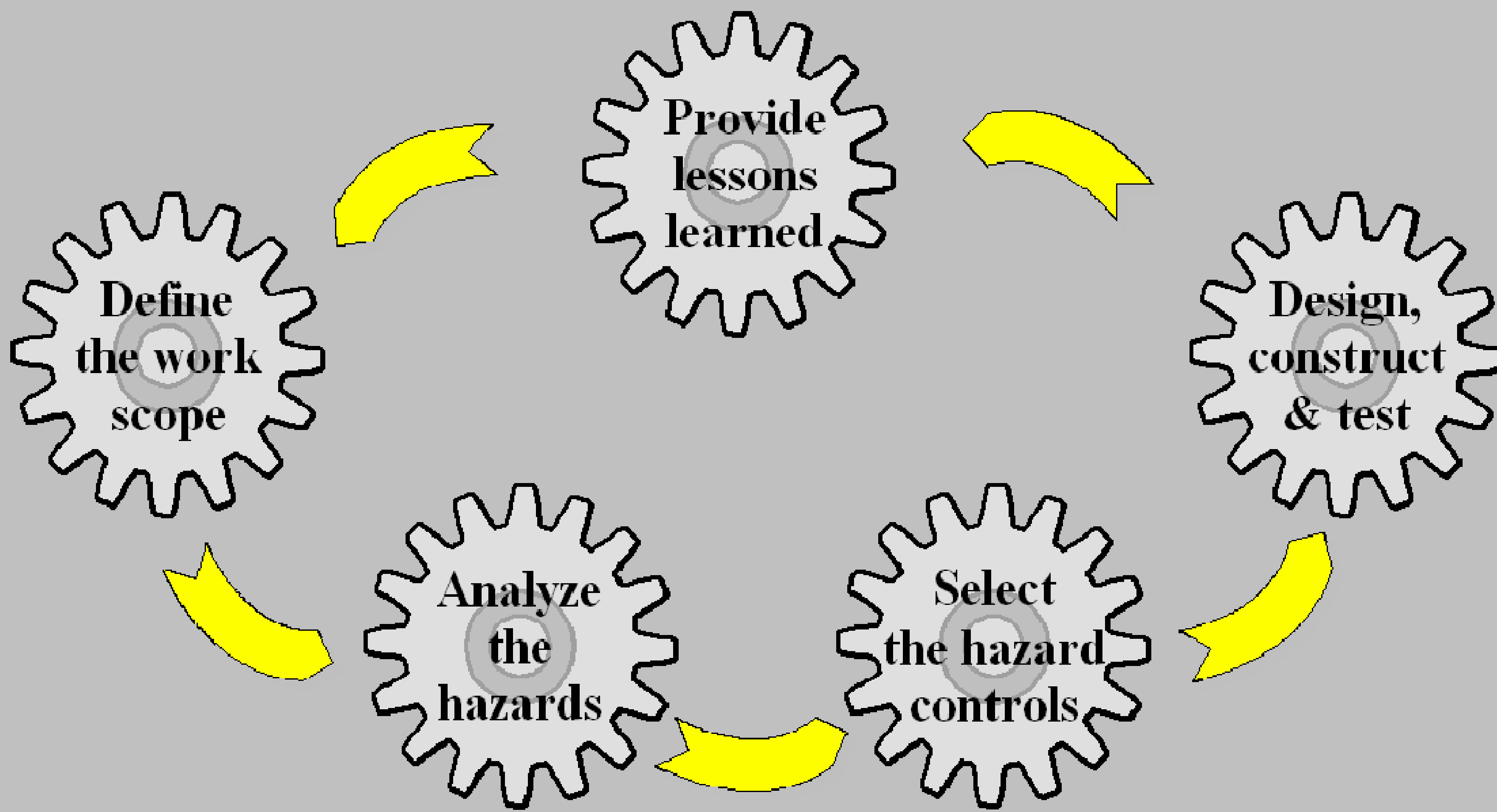
Overview of Presentation

- Hydrogen – What makes hydrogen unique?
- Definitions – Keeping everyone on the same page.
- Recap from 2005 Safety Analysis Results
- Description of Design Options
- Comparisons of Design Options
- Report Summary

Why is Hydrogen Unique?

- An extremely light gas
- Leaks readily dissipate
- Will leak through very small openings
- Not usually odorized
- Flames are invisible
- Lower flammability limit is 4%
- Low ignition energy

Definitions - Managing the Process



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Definitions - Evaluation Criteria

Frequency → / Consequence	Beyond extremely unlikely	Extremely unlikely	Unlikely	Anticipated
High		7	4	1
Moderate	10	8	5	2
Low		9	6	3
Negligible	11		12	

- High risk
- Moderate risk
- Low risk
- Negligible risk

Definitions - Consequence

Consequence Level	Impact on Populace	Impact on Property and Operations
High (H)	Prompt fatalities Acute injuries	Damage > $5 million Production loss > 1 week
Moderate (M)	Serious injuries Non-permanent injuries Hospitalization required	$100,000 < damage < $5 million Vehicle destroyed Critical equipment damaged Production loss < 1 week
Low (L)	Minor injuries	Damage < $100,000 Repairable damage to vehicle Significant operational down time
Negligible (N)	Negligible injuries	Minor repairs to vehicle Minimal operational down time No impact on surroundings

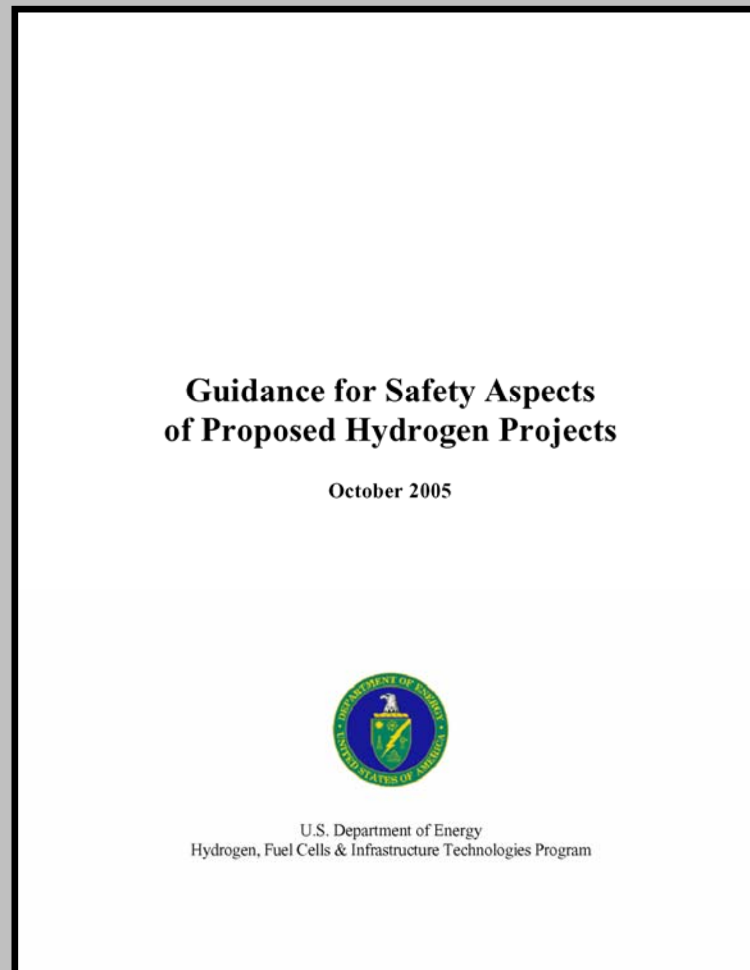
Definitions - Frequency

How often does the loss occur (events/year)

Acronym	Description	Frequency level
A	Anticipated, Expected	$f > 10^{-2}$ /yr
U	Unlikely	$10^{-4} < f < 10^{-2}$ /yr
EU	Extremely Unlikely	$10^{-6} < f < 10^{-4}$ /yr
BEU	Beyond Extremely Unlikely	$f < 10^{-6}$ /yr

Safety Analysis – Why Required?

- Must answer
  - Is it safe?
  - Are there safety-related design requirements?
  - What procedures are required?
- Limit safety risk
- Limit project risk
- DOE requires one


Guidance for Safety Aspects of Proposed Hydrogen Projects

October 2005

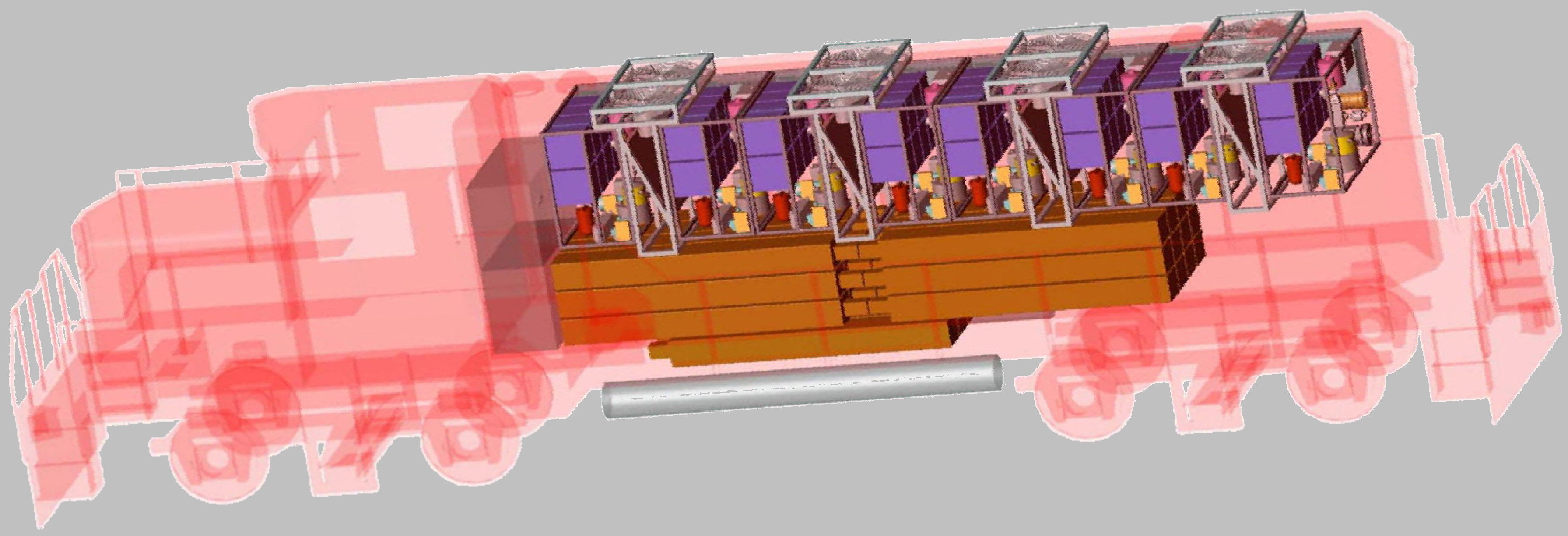
U.S. Department of Energy
Hydrogen, Fuel Cells & Infrastructure Technologies Program

DOE Safety Plan Requirements

- Identification Safety Vulnerabilities (ISV) = SA
- Risk Mitigation Plan
  - Safety performance metrics
  - Safety basis management (change control)
  - Control summary (procedures, training & equipment)
  - Emergency response plan
- Preparation of a Communication Plan
  - Safety reviews during design
  - Incident reporting

HA Base Case – Metal Hydride Storage

- Draft SA (ISV) was prepared in 2005
- HA Scope
  - Metal hydride fuel system
  - 250 kg hydrogen capacity
  - About 10 % available for immediate release



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Hazard Analysis (ISV) Status

Mode	Hazard Identification	Hazard Evaluation	Control Section
Operating	Draft	Draft	Draft
Storage	Draft	Draft	...
Maintenance	Draft	...	...
Refueling	Draft	...	...

SA Results for Hydride Concept

◆ **Modes of Use**	**4**
▪ Operation (OP)	
▪ Storage (ST)	
▪ Maintenance (MA)	
▪ Refueling (RE)	
◆ **Hazards Identified**	**146**
◆ **OP Scenarios**	
▪ High Risk Events	6
▪ Medium Risk Events	31
▪ Low Risk Events	5
▪ Negligible Risk Events	1
▪ Total	43

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SA Results for Hydride Concept (con't)

High risk OP events that require further evaluation

- Fire
  - High risk dominated by potential for property loss. Need to establish if acceptable or if additional protection should be provided.
- Explosion
  - Gas detection, secondary enclosures, maintenance & inspection reduce the risk.   Need to evaluate additional controls.
- Electrocution
  - High risk dominated by potential for worker injury. Warning signs, locking cabinets and training reduce risk. Need to evaluate additional controls.

SA Results for Hydride Concept (con't)

Potential resolutions for high risk events

- **Fire**
  - Number of events — 5
  - Consequence — High
  - Frequency — Unlikely
- **Explosion**
  - Number of events — 1
  - Consequence — High
  - Frequency — Unlikely
- **Electrocution**
  - Number of events — 1
  - Consequence — High
  - Frequency — Unlikely

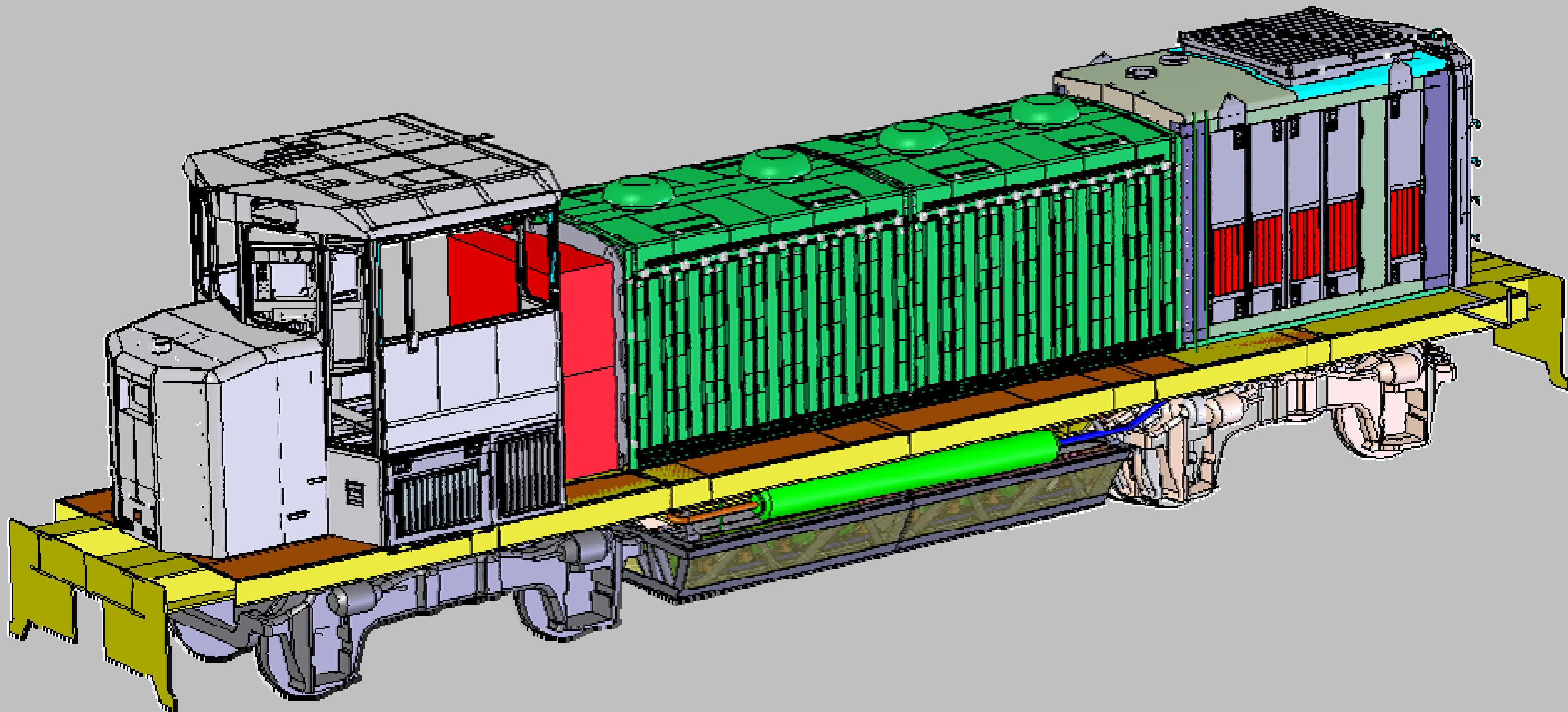
Ballard Power System P5 Program Experience

- Highlights
  - Number of buses: 39
  - Number of cities: 13
  - Hours in operation >100,000
  - Number of riders: 5,000,000
  - Distance traveled: > 1,500,000 km
- EU Sites:
  - Madrid, Hamburg, London, Amsterdam, Barcelona, Stockholm. Reykyavik, Luxembourg, Stuttgart & Porto
- Other Sites:
  - Santa Clara, California
  - Perth, Australia
  - Beijing, China

Ballard Power System Experience (con't)

- No explosions or serious fires have occurred.
- The more common incidents include:
  - Minor fuel leaks
  - Nozzle leaks
  - Fueling hose leaks
  - Minor accidents (no injuries)
  - Coach issues (doors, tires)
- Safety incidents are more common with the fueling station & station interface
- Incidents with vehicle and FC engine are less common

Option 1 - Undercarriage H2 Mounting



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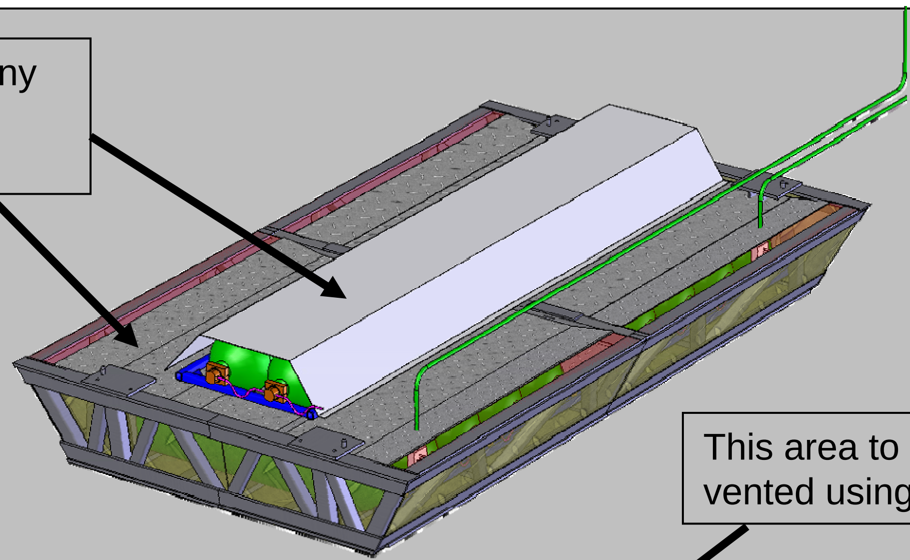
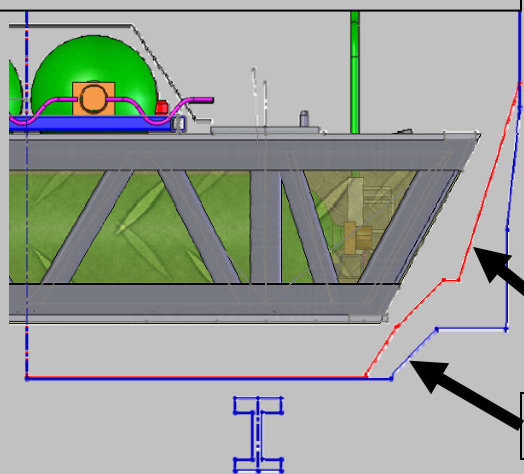
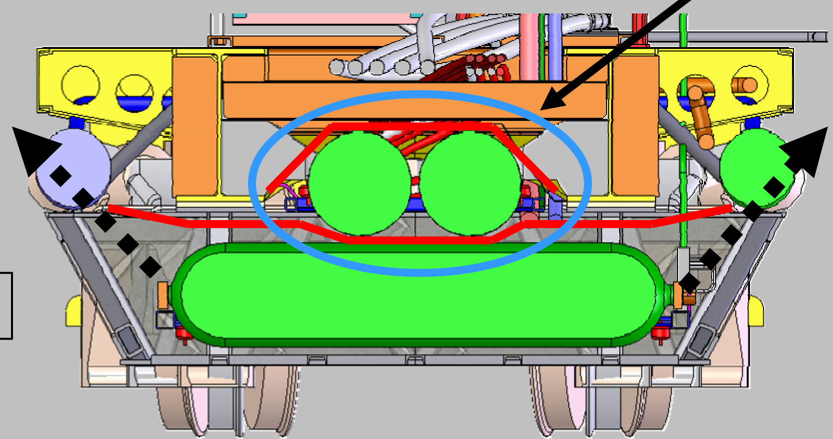
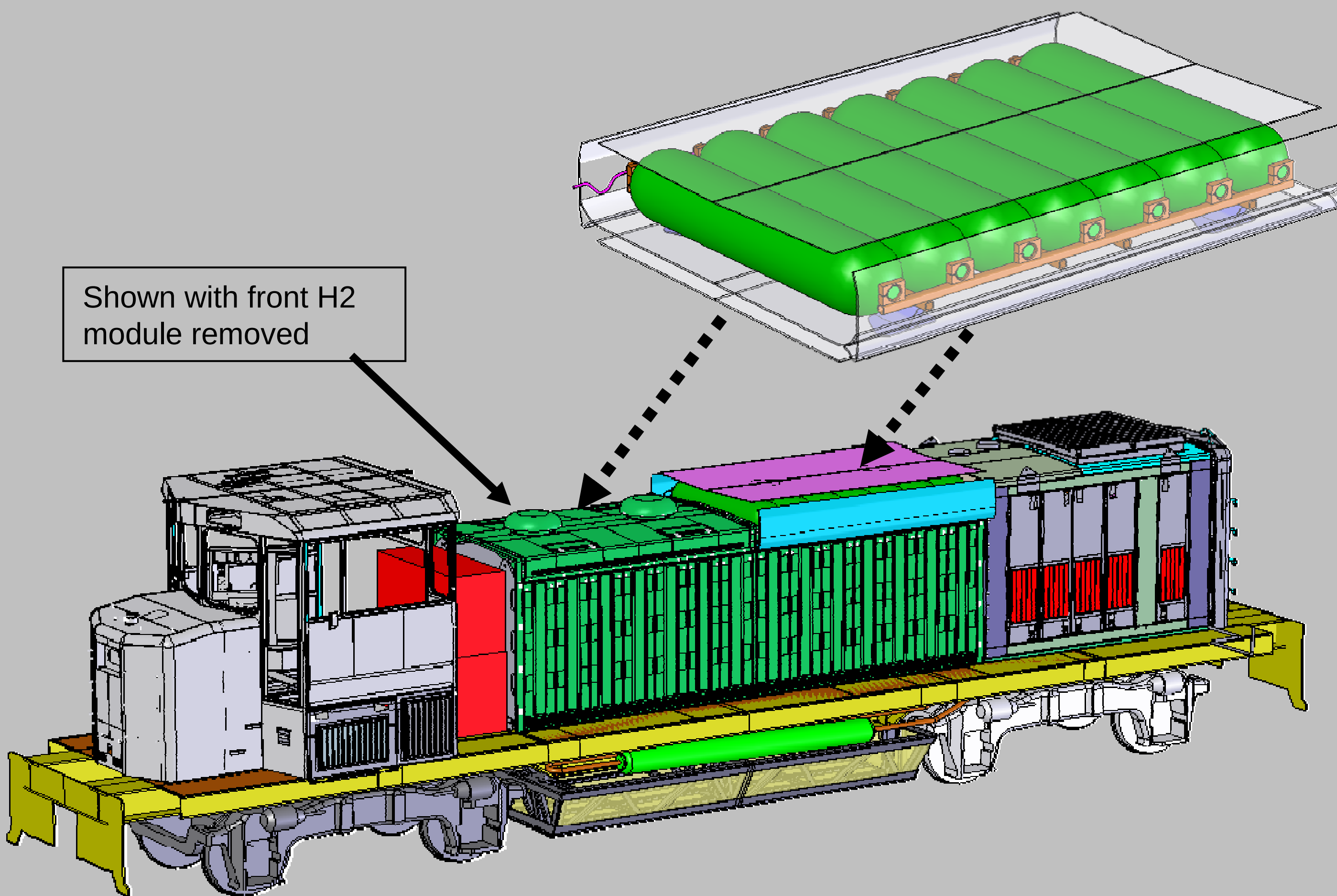
Option 1 - Undercarriage H2 Mounting (con't)





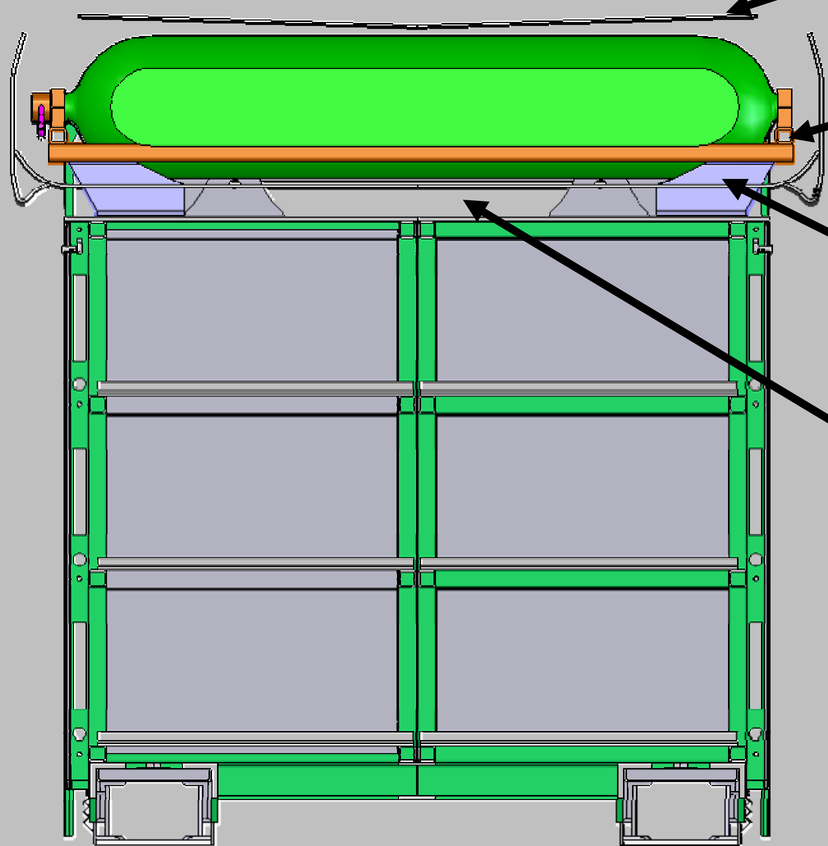


Option 2 – Roof Top H2 Mounting



Washington Group International

Option 2 – Roof Top H2 Mounting (con't)



TOP COVER

H2 TANKS MOUNTED ORANGE FRAME – FRAME BOLTS TO PURPLE BRACKETS

BARRIER SHIELD AND PURPLE BRACKETS BOLT ONTO TO BATTERY RACK

AIR CHANNEL – 3.5" BETWEEN BARRIER SHIELD AND TOP OF BATTERY RACK

Washington Group International

Design Highlights

	On-board hydrogen	Available for immediate release during operation
Baseline (Metal Hydride)	250 kg	~ 25 kg
Option 1, Gaseous Storage Under Locomotive	70 kg	70 kg
Option 2, Gaseous Storage Above Locomotive	70 kg	70 kg
Option 3, Metal Hydride Under Locomotive	63 kg	~ 6 kg

Summary of HA Results

- Baseline (Metal Hydride)
  - Modes of operation 4
  - Hazards identified 146
  - Scenarios for operation mode 43
- Option 1, Gaseous Storage Under Locomotive
  - Modes of operation 4
  - Hazards identified: add 1, remove 2 145
  - Scenarios for operation mode 43
- Option 2, Gaseous Storage Above Locomotive
  - Modes of operation 4
  - Hazards identified: add 1, remove 2 145
  - Scenarios for operation mode 43

Summary of HA Results – Fire Events

- **Primary event: OP1-1, OP1-2, OP1-3, OP3-2 & OP5-4**
  - Fire involving locomotive (may involve hydrogen system)
- **Unmitigated Result**
  - Frequency — Anticipated
  - Consequence (worker, public, property) — High
  - Risk — High
- **Mitigated Result**
  - Frequency (worker, public, property) — A, U, U
  - Consequence (worker, public, property) — M, L, H
  - Risk — M, L, H
- **Concepts**
  - Limit ignition sources
  - Move workers & public away from fire

Summary of HA Results – Explosion Event

- **Primary event: OP2-5**
  - **Accidental release of hydrogen with explosion (deflagration or detonation)**
- **Unmitigated Result**

Frequency	Anticipated
Consequence	High
Risk	High

- **Mitigated Result**

Frequency	Unlikely
Consequence	High
Risk	Moderate

- **Concepts**
  - **Prevent release**
  - **Limit ignition sources**

Comparisons of fuel storage options

(Lower number is preferred)	Base Case (Metal Hydride)	Option 1 (gas below)	Option 2 (gas above)
Open air deflagration	1	2	2
Open air detonation	BEU	BEU	BEU
Confined deflagration	1	3	2
Confined small detonation	2	3	1
Confined large detonation	1	3	2
Totals	5	11	7

Explosions – Ignition Under Locomotive

- Estimate an approximate damage radius
  - Explosion occurs under locomotive chassis (Open air of less concern)
  - Base on the TNT Equivalent Method
- Assumptions
  - Stoichiometric concentration of hydrogen under the locomotive chassis
  - Volume under locomotive to be 10 m^3 (8' x 30' x 1.5')
  - Explosion efficiency = 0.3 (typical value is 0.05 for open air event)
  - 1 psig overpressure is the acceptance level

Explosions – Damage thresholds

Overpressure (psig)	People	Property
0.5 to 1	Low potential for direct injury	Windows usually shattered; some window frame damage
2	Potential for temporary hearing loss & indirect injuries	Partial collapse of walls and roofs of wood frame structures
5 to 7	Threshold for eardrum rupture	Nearly complete destruction of houses
10	Threshold for serious lung damage	Probable total building destruction

Explosions – Ignition Under Locomotive (con't)

- **TNT Equivalent Method**
  - **Volume under locomotive = 10 m^3**
  - **Stoichiometric quantity of hydrogen = 0.6 kg**
  - **The equivalent TNT quantity = 4.6 kg**
  - **Result = 1 psig at 80 feet**
    (Partial demolition of wood structures)
- **Very conservative result**
  - **Available volume is overstated**
  - **Explosion efficiency taken as 0.3 vs. typical 0.05**
  - **Damage threshold is taken as 1 psig**