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Maritime Fuel Cell Generator Project

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Abstract

A first-of-its kind hydrogen fuel cell power generator for marine applications was designed, built, and demonstrated to verify increased energy efficiency at part loads and reduced emissions. The project goals were to demonstrate the use of the generator in the maritime environment, identify areas requiring additional research and development, analyze the business case, and address regulatory and other market barriers.

A 100 kW generator with 72 kg of hydrogen storage was designed and built by Hydrogenics with safety and regulatory reviews by the Hydrogen Safety Panel, US Coast Guard, and American Bureau of Shipping. Young Brothers operated the generator for 10 months powering refrigerated containers in Honolulu, HI.

The project showed it is possible to increase energy efficiency by up to 30% at part load and reduce emissions to zero through the use of hydrogen fuel cells, and identified paths forward to wider adoption of the technology in this sector.

Acknowledgements

The authors wish to acknowledge both the US Department of Energy (DOE), Fuel Cell Technologies Office (FCTO) within DOE's Office of Energy Efficiency and Renewable Energy, and the US Department of Transportation (DOT), Maritime Administration (MARAD), Maritime Environmental and Technical Assistance (META) program for sponsoring this effort. In particular, the authors thank both project managers, Pete Devlin at FCTO and Sujit Ghosh at MARAD, for enthusiastically providing their support, guidance, and technical expertise throughout the project.

While this report is written by Sandia, it summarizes a project which was performed by fourteen partner organizations. The authors would like to acknowledge the following individuals, in addition to Pete and Sujit, who provided significant time and effort to help make the project a success:

- *Mahalo* to all the friendly, helpful, hardworking staff at Young Brothers: Glenn Hong, Nami Ohtomo, Gavin Calimpong, Dave Holland, Chris Martin, Matt Humphrey, Mac MacDonald, Roy Catalani, Dean Kapoi, Loi Rivera, Damien Soares, John Min, Troy Achiu, Kenny Risso, Bob Ray, Joy Aipoalani, Nathan Kapule, and Eddie Magaoay.
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- US Hybrid/Hickam Station: Rusty Hughes, Abas Goodarzi
- Hawaii Natural Energy Institute: Mitch Ewan
- Pacific Northwest National Laboratory: Nick Barilo, Monte Elmore
- California Fuel Cell Partnership: Jennifer Hamilton
- Blue Planet Research: Paul Ponthieux
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- American Bureau of Shipping: Prasad Mantravadi, Michael Wasicek
- Sandia National Laboratories: Billy Thomas, Chris LaFleur, Myra Blaylock, Ethan Hecht, David Rose, Bruce Balfour, Jill Micheau, Landon Daft, Lynn McClellan

Without each of these individuals contributing their best this project would not have been possible.

Executive Summary

Fuel costs and emissions in maritime ports are an opportunity for transportation energy efficiency improvement and emissions reduction efforts. Ocean-going vessels (OGVs), harbor craft, and cargo handling equipment are still major contributors to air pollution in and around ports. Diesel engine costs continually increase as tighter criteria pollutant regulations come into effect and will continue to do so with expected introduction of carbon emission regulations. Diesel fuel costs will also continue to rise as requirements for cleaner fuels are imposed. Both aspects will increase the cost of diesel-based power generation on the vessel and on shore.

Hydrogen fuel cells have a long track record of supplying efficient, clean power for a wide range of applications, including forklifts, emergency backup systems, and vehicles. They have the potential to meet the electrical demands of vessels in the port as well as supply power for other port uses such as yard trucks, forklifts and other material handling specialty equipment, and refrigerated containers (reefers). Hydrogen fuel cells produce zero emissions at the point of use. They have inherent energy efficiency advantages from both an overall efficiency standpoint (Carnot Law) and at part loads due to the diverging efficiency characteristics of fuel cells and diesel engines as load is reduced. These characteristics reduce the overall amount of fuel needed for power production when diesel engine generators operate at part load (as is typically the case).

Although fuel cells have been used in many successful applications, they have not been technically or commercially validated in the port environment. One opportunity to do so was identified in Honolulu Harbor at the Young Brothers Ltd. (YB) wharf. At this facility, barges sail regularly to and from neighbor islands and containerized diesel generators provide power for the reefers while on the dock and on the barge during transport, nearly always at part load. Due to inherent efficiency characteristics of fuel cells and diesel generators, switching to a hydrogen fuel cell power generator was found to have potential emissions and cost savings.

Based on this potential benefit, Young Brothers agreed to host a hydrogen fuel cell generator and utilize it in the same way they use their existing diesel generators, powering reefers on the dock and on interisland barges. The project benefits outside of Young Brothers include the lowering of technological and business risk for future adopters of the technology by demonstrating the satisfactory use of the generator in the port environment and by feeding back to the DOE R&D programs, analyzing the real-world business case, as well as addressing regulatory and other market barriers to widespread adoption.

The first-of-its-kind generator (Figure ES-1) was designed and built by project partner Hydrogenics to the technical specifications determined jointly by the project team. It consists of a 20-foot ISO standard "hi-cube" shipping container and contains the proton exchange membrane fuel cell rack, power inverter, ultracapacitors for short term transient loading, cooling system, hydrogen storage, and system controller and data acquisition equipment. The system contains 72 kg of hydrogen at 350 bar and has a rated power of 100 kW, 240 VAC 3-phase, which can be divided among 10 plugs to power up to 10 reefers at a time. The design of the generator was reviewed by the US Coast Guard, American Bureau of Shipping, and the Hydrogen Safety Panel to ensure safety and compliance with regulations.

Figure ES-1: The maritime fuel cell generator, with integrated hydrogen storage, PEM fuel cell power generation, and power inverter equipment can power up to 10 reefers with a total rated output of 100 kW at 240 VAC.

Prior to demonstration of the generator at the site, the project team performed on-site technical and safety assessments of the Young Brothers operation to develop site-specific operational safety requirements, operational instructions and procedures for operation and fueling, and emergency response procedures. Project partner Pacific Northwest National Laboratories conducted on-site training on hydrogen familiarity (for employees) and emergency response (for local first responders).

An important accomplishment of this project was the bringing together of relevant regulatory entities and public safety stakeholders to ensure compliance with regulatory intent in the absence of specific regulations or codes governing the design and use of the generator in a maritime environment (at the port or on the barge). Many of these entities were exposed to the details of hydrogen and fuel cell technology for the first time, but the collaborative approach and efforts of all project partners using their various strengths to interact with these stakeholders led to immediate adoption and use of the generator by the deployment host once it arrived on site.

The generator began operation in August, 2015 with on-site commissioning. The commissioning process identified several technical issues with the generator that were corrected during the month of August, and once complete, the generator was handed over to Young Brothers for full use.

The generator was filled with hydrogen provided by Hickam Air Force Base without charge, with project partner Hawaii Center for Advanced Transportation Technologies (HCATT) as the prime contractor of the Hickam hydrogen station. When fueling was needed, the generator was loaded onto a chassis (wheeled frame trailer) and trucked to Hickam, about 7 miles from Young Brothers, where the station operator would perform the fill in about 20-30 minutes. The generator was trucked back to Young Brothers and off-loaded for continued use. Each of the eight fills during the deployment period was conducted smoothly and without any problems, dispensing a total of 428 kg into the generator.

From the period of August, 2015 to June, 2016 the generator was used by Young Brothers on 52 different days for a total of 278 hours. It averaged 29.4 kW (gross) during this period for a total energy generation output of 7,285 kWhr and achieved a 5-minute continuous peak power of 91.3 kW (gross). Its net energy efficiency ranged from 36% to 54% over the load range of 16% to 62%. By comparison, the net efficiency of a comparable diesel generator efficiency is from 25% to 34% in this same load range. Using no diesel fuel and producing zero emissions at the point of use, during the demonstration period the fuel cell generator displaced 865 gallons of diesel fuel, over 16 MT of CO_2 emissions, and avoided nearly 150 combined kilograms of criteria pollutants (NOx, CO, HC, PM, and SOx) as compared to an existing Young Brothers 350 kW Tier 3 diesel generator.

The deployment experienced numerous technical issues with the generator that limited its use. The primary technical issue during the deployment was an inconsistent startup which was attributed to a communication problem between the overall system controller, inverter, and fuel cell rack. This in turn led to problems with draining of the startup battery, and the overall result was many aborted attempted starts and non-use until the problem could be identified and fixed. The generator's fuel cells also experienced higher-than-anticipated consumption of DI water, which was exacerbated by the high ambient temperature along with a small DI water reservoir, causing the operators to have to fill the reservoir more than expected. The consumption was within specification of the fuel cells and not a serious issue, but nonetheless was an unanticipated inconvenience. The generator did not experience any safety-related events and did not exhibit any serious signs of wear or deterioration in the seaport environment. The technical lessons learned from the deployment will be used by the manufacturer to modify this generator for subsequent testing as well as to improve next generation products.

One objective of this deployment was to gather "real-world" experience with operating hydrogen fuel cell equipment. A flawlessly operating generator would likely have been integrated smoothly into the existing Young Brothers operations. However the technical issues meant that time needed to be spent by Young Brothers staff to assist in troubleshooting and performing minor maintenance. Many times, Young Brothers staff was not available due to numerous other activities needed to maintain normal operation of the facility. The testing revealed that a dedicated operator would have been needed to maintain continuous operation of the generator because of its technical issues.

The capital and operating costs of the hydrogen fuel cell generator were determined for three cases: (1) the deployment, (2) a notional deployment with full usage, and (3) a future deployment where fuel cell and hydrogen costs have come down. These were compared to that of a diesel generator at current costs of equipment and fuel. This presents a worst-case scenario for the fuel cell generator since expected stricter emissions regulations and increase fossil fuel costs are expected in the future (e.g. a doubling of today's diesel fuel cost in 10 years[1]), the result being continually higher diesel equipment and fuel costs as time goes on.

The analysis showed that even with fuel cell costs reaching the DOE target of $50/kW, the capital cost of the generator system is projected to remain three-times higher than today's comparable diesel

[1] U.S. Energy Information Administration, "Nominal Petroleum Prices : Transportation : Diesel Fuel, Reference, AEO2017," EIA Open Data – Intro, accessed April 2017. http://www.eia.gov/opendata/.

generator due to the balance of plant. Large portions of the balance of plant cost are the power conditioning (inverter) and hydrogen storage tubes, where future cost reductions (to approximately 1/3 of today's costs) are necessary to enable competitiveness. The analysis also revealed that fuel is the major operating expense for these systems. While this demonstration enjoyed free fuel from the Hickam station, that will not be the case in true commercial adoption. Today's difference in hydrogen costs (high) and diesel costs (low) is expected to significantly decrease in the future as hydrogen costs decrease and diesel costs increase, but the current differential hinders the ability of today's fuel cell systems to achieve cost parity with today's diesel systems.

As the first validation of a self-contained hydrogen fuel cell generator at a port, this project showed that it is possible to reduce maritime-related emissions through the use of hydrogen fuel cells, and identified paths forward to more widespread adoption of the technology in the marine sector. This includes not only the use of a generator for reefer power but other applications as well. These include port equipment, electrical resiliency against grid outages, auxiliary power for vessels, and vessel propulsion power. Establishing hydrogen equipment usage at port also has the benefit of establishing a local hydrogen infrastructure hub that can be leveraged to provide hydrogen for regional transportation uses. Future usage of the generator by other hosts will continue to collect the information needed to completely assess the business case as well as provide opportunity for continued development of the technology.

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Nomenclature

ABS	American Bureau of Shipping
AHJ	Authority Having Jurisdiction
BLS	Bureau of Labor Statistics
BOP	Balance of Plant
CO_{2eq}	Equivalent CO_2 (emissions)
CR	Concentration-response
DI	Deionized (Water)
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
FAR	Fatal Accident Rate
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCPR	Fuel Cell Power Rack
FMEA	Failure Modes and Effects Analysis
GWP	Global Warming Potential
HC	Hydrocarbon
HCATT	Hawaii Center for Advanced Transportation Technologies
HNEI	Hawaii Natural Energy Institute
HSP	Hydrogen Safety Panel
HVAC	Heating, Ventilation, and Air Conditioning
IEC	International Electrotechnical Commission
IFC	International Fire Code
ISO	International Standards Organization
MARAD	Maritime Administration
MarFC	Maritime Fuel Cell
MBA	Marginal Benefit of Abatement
MEA	Membrane Electrode Assembly
MO	Machine Operator
NFPA	National Fire Protection Association
NGV	Natural Gas Vehicle
NRTL	Nationally Recognized Testing Laboratory
OGV	Ocean Going Vessel
OSC	Overall System Controller
P&ID	Piping and Instrumentation Diagram
PEM	Proton Exchange Membrane
PM	Particulate Matter
PNNL	Pacific Northwest National Laboratory
PRV	Pressure Relief Valve
QRA	Quantitative Risk Assessment
ULSD	Ultra Low Sulfur Diesel
USCG	United States Coast Guard
VAC	Volts – Alternating Current
VRLA	Valve Regulated Lead Acid
YB	Young Brothers

1 Project Description

This chapter gives an overview of the project, its partners, goal, method, and content of this report.

1.1 Overview

This project accomplished the development and deployment of a nominally 100 kW, integrated fuel cell prototype for marine applications.

The benefits of this project include:

- Lowering the technology risk of future port fuel cell deployments by providing performance data of H2-proton exchange membrane fuel cells (PEMFC) technology in this environment.
- Lowering the investment risk by providing a validated business case assessment for this and future potential projects.
- Enabling easier permitting and acceptance of H2-Fuel Cell (H2-FC) technology in maritime applications by assisting US Coast Guard (USCG) and maritime Class Societies (American Bureau of Shipping) to develop and prove hydrogen and fuel cell codes and standards.
- Acting as a stepping stone to enable shipboard fuel cell deployments.
- Maintaining hydrogen fuel cell capability in the state of Hawaii in support of future fuel cell electric vehicle (FCEV) rollout.
- Providing user experience with hydrogen and fuel cell technology in the maritime and port sector, increasing the knowledge base and helping to establish a trained workforce.
- The potential for cost savings for the operator. It is estimated that replacement of six 300 kW diesel generators with fuel cell systems could save from $100,000 to $600,000 (depending on actual fuel costs) in diesel per year.
- The potential for emissions savings at the port. Under the same scenario as above, over 650,000 kg CO_2, 3,300 kg NO_x, 2,700 kg CO, 190 kg HC, 90 kg PM, and 14 kg SO_x per year will be avoided by using fuel cell generators instead of current technology resulting in an economic benefit to society.

Although no fuel cells had been tested specifically at a port before, prior success with hydrogen fuel cell demonstrations such as telecom backup power, mobile construction equipment, and industrial trucks, including operation in the vicinity of the ocean, lowered the risk with regard to the technical viability of fuel cells in this environment. Validation of the commercial value proposition of both the application and the hydrogen supply infrastructure is the next step towards widespread use of hydrogen fuel cells in the maritime environment. This is determined by meeting necessary equipment and operating costs and customer expectations such as reliability, form and function..

1.2 Goal

The goal of this project was to:

Develop a fuel cell system for the marine environment that will reduce emissions and be a viable, affordable, competitive alternative to diesel-based systems.

1.3 Partners

This project brought together industry partners in this prototype development as a first step towards eventual commercialization of the technology. To be successful, the project incorporated interested industry and regulatory stakeholders: an end user, technology supplier and product integrator, and land- and maritime-based safety and code authorities. Project costs were shared by the primary stakeholders in the form of funds, in-kind contribution, and material/equipment either loaned or donated to the project. Project partners and roles were:

- **U.S. Department of Energy**: sponsorship and steering
- **U.S. Department of Transportation - Maritime Administration**: sponsorship and steering, facilitation of maritime relationships
- **Sandia National Laboratories**: management and coordination, hydrogen supply and systems, safety and risk analyses, data collection and technical and business case assessment
- **Young Brothers, Ltd.** and **Foss Maritime**: Site host, prototype operation, routine maintenance
- **Hydrogenics**: Design, engineer, build, commission, and support the prototype generator
- **Hawaii Natural Energy Institute**: Facilitation with local hydrogen supply and logistics
- **Hawaii Center for Advanced Transportation Technologies**: Hydrogen provider
- **U.S. Coast Guard**: Review and acceptance of generator design and operation
- **American Bureau of Shipping**: Review and input of prototype design to maritime product standards.
- **Pacific Northwest National Laboratory**: Prototype and project safety review by the Hydrogen Safety Panel; provider of Hydrogen Emergency Response Training for First Responders

1.4 Approach

The project was divided into four phases:

1. Establishment and specification
2. Detailed design and engineering
3. Generator fabrication/site construction
4. Deployment (on-site demonstration)

1.4.1 Phase 1: Establish Project Team and Define Generator Specifications

In Phase 1, the stakeholders were finalized and together determined the specifications and high-level design features of the generator.

1.4.2 Phase 2: Design and Engineering of the Generator and the Site

In Phase 2, two parallel and connected engineering efforts were accomplished. The first effort, funded jointly by DOE and MARAD, and utilizing industry cost-share, was design and engineering of the prototype unit to meet the specifications determined in Phase 1. This included fuel cell system selection, design of the thermal management system, selection of the hydrogen storage system and interconnection methods, specification and integration of power conversion equipment, in-container safety system design, container design, and integration of all components into the container. Generator design was reviewed by the Hydrogen Safety Panel, the U.S. Coast Guard, and the American Bureau of Shipping.

In parallel, the site at Young Brothers was prepared to receive the demonstration unit. This activity included hydrogen supply logistics, site permitting and safety analyses and acceptance, and preparations for operations and maintenance. Phase 2 also included development of a data collection and analysis plan.

1.4.3 Phase 3: Generator Fabrication and Site Preparation

Using the design from Phase 2, the generator was fabricated at Hydrogenics' manufacturing facility, factory tested, and sent to YB for deployment.

In parallel, the site preparation and hydrogen supply activities were completed. This included conducting hydrogen familiarity, safety, and firefighting training for YB personnel, local First Responders, and other stakeholders in coordination with DOE's Hydrogen Safety Panel.

1.4.4 Phase 4: Deployment of the Generator

The project team commissioned the prototype at YB and transitioned operational control to YB. Hands-on operational and routine maintenance training was given to YB personnel. YB operated the prototype for ten months at the dock. Sandia and other stakeholders continued to provide technical support, and collect and analyze data throughout the deployment

1.5 Content of the Report

This report captures the data collected during operation to assess the generator's technical performance and business value proposition and to provide critical lessons learned during all project phases for follow-on deployment and commercialization efforts.

The report is divided into seven chapters. Chapter 2 describes the background and rationale for the deployment. Chapter 3 describes the design and operational and safety features of the generator and Chapter 4 discusses the regulations, safety considerations, and procedures for operating the generator at the host site. Chapter 5 discusses the technical performance of the generator during the deployment while Chapter 6 presents the economic evaluation. The report concludes with lessons learned and recommendations in Chapter 7.

2 Background

This chapter consists of two parts. The first part describes the need and opportunity for replacement of diesel generators at ports for fuel use reduction and elimination of emissions. The second part describes the existing operations at Young Brothers in Honolulu, HI and their suitability to be the initial host for deployment of this technology in order to verify its characteristics in a port environment.

2.1 Fuel Cells as Diesel Generator Replacements at Ports

Fuel costs and emissions in maritime ports are an opportunity for transportation energy efficiency improvement and emissions reduction efforts. For example, a 2004 study showed the Port of Los Angeles had average daily emissions exceeding that of 500,000 vehicles.[1] Efforts have been underway to reduce these emissions from all sources, but ocean-going vessels (OGVs), harbor craft, and cargo handling equipment are still major contributors to air pollution in and around ports. Approximately one-third to one-half of emissions attributed to OGVs comes from their auxiliary diesel engines which are run while the vessels are at berth (docked) and require electrical power for refrigerated containers, lighting, loading/discharging equipment, and other uses.[2] Diesel engine and fuel costs continue to rise as emissions limits are imposed, making diesel-based power generation on the vessel and on shore more expensive for fleets.[3]

Hydrogen fuel cells have a long track record of supplying efficient, clean power for a wide range of applications, including forklifts, emergency backup systems, and vehicles. They have the potential to meet the electrical demands of vessels in the port as well as supply power for other port uses such as yard trucks, forklifts and other material handling specialty equipment, and refrigerated containers. Hydrogen fuel cells produce zero pollutant emissions and no greenhouse gases at the point of use and can reduce the overall amount of diesel or other maritime fuel used. Therefore a hydrogen infrastructure system established at a port can meet most if not all port operational requirements while at the same time also meeting emerging environmental requirements. Although fuel cells have been used in many successful applications, they have not been technically or commercially validated in the port environment.

A 2013 Sandia National Laboratories' report, "Vessel Cold-Ironing Using a Barge Mounted PEM Fuel Cell: Project Scoping and Feasibility," [3] identified several opportunities for demonstrating technical and commercial viability of a fuel cell in the maritime environment. One opportunity identified was in Honolulu Harbor at the Young Brothers Ltd. (YB) wharf. At this facility barges sail regularly to and from neighbor islands and containerized diesel generators provide power for the reefer containers while on the dock and on the barge during transport. The company is strongly interested in reducing its cost of fuel and a containerized hydrogen fuel cell power generator capable of replacing current diesel generators has the potential to be a viable solution.

Using hydrogen fuel cells to replace diesel generators has been examined before. A 2012 Sandia report, "Analysis of H2 Storage Needs for Early Market Non-Motive Fuel Cell Applications," [4] identified portable diesel generators in the 15 kW to 150 kW range to be an attractive potential replacement application for hydrogen fuel cells. The market potential for this product is illustrated in data from 2008 presented in Figure 1, showing that this power segment is the largest market above 10 kW.

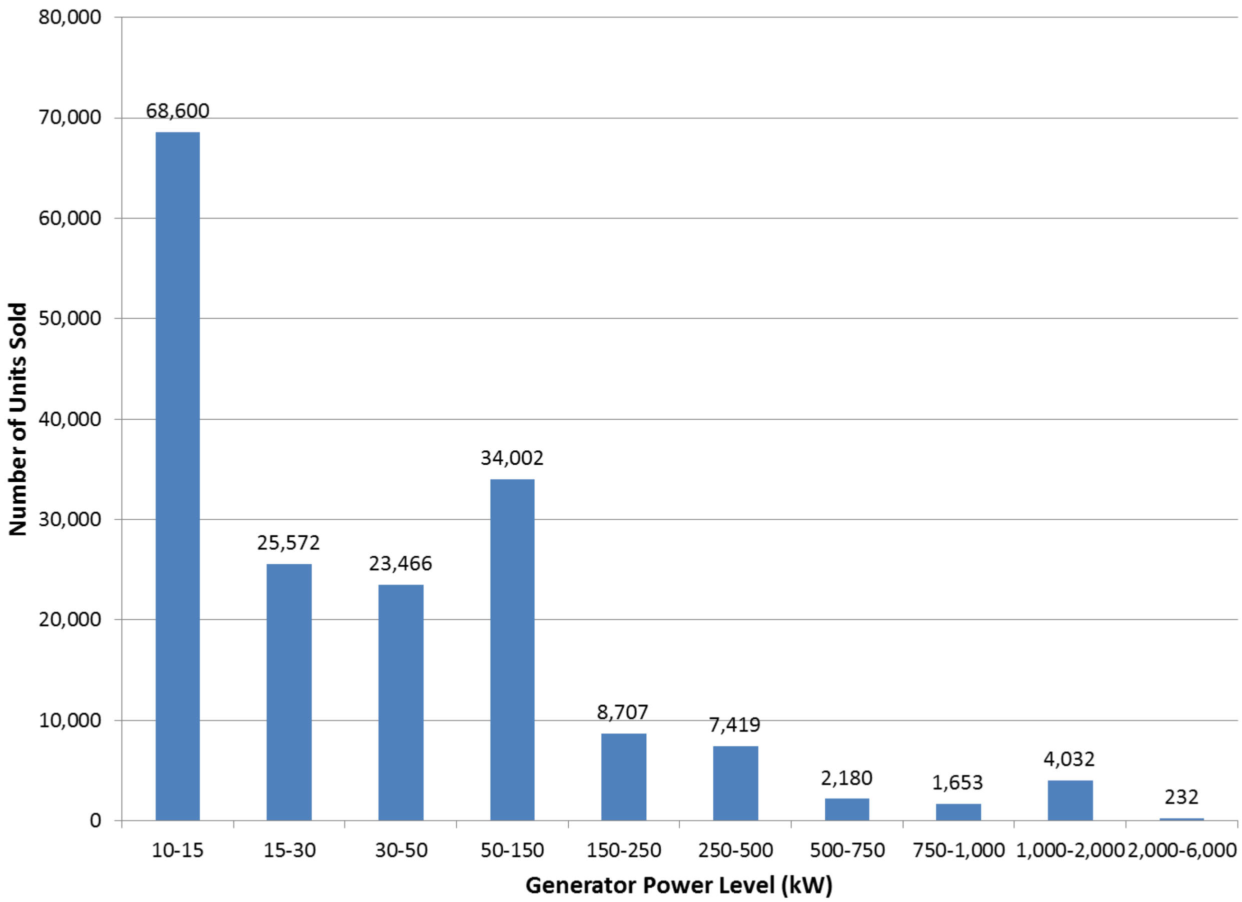

Figure 1: North American generator sales in 2008, by power level. Generators below 10 kW are excluded since they are primarily gasoline-powered. Many 10-15 kW generators are also gasoline powered. Data from Power Systems Research OE Link database available at: www.powersys.com/oe-link.

Feedback from stakeholders during development of this 2012 study revealed that generators are frequently operated at part load. Generator sizes are specified by the end user based on a maximum possible power need based on maximum attached circuit ratings. This sets the 100% load point, and is rarely encountered in practice for any appreciable length of time. Operation at part load results in many issues for diesel generators. In addition to increased specific fuel consumption (lower efficiency) and increased pollutant emissions, operating a diesel genset at part load has the following maintenance issues [5]:

- Hydrocarbon build-up
- Rings sticking
- Glazed piston and cylinder walls
- “Slobbering” or “wet-stacking” (appearance of oil droplets in exhaust)
- Burning oil

Each of these issues increases maintenance frequency and cost, reduces time between overhauls, and shortens engine life.

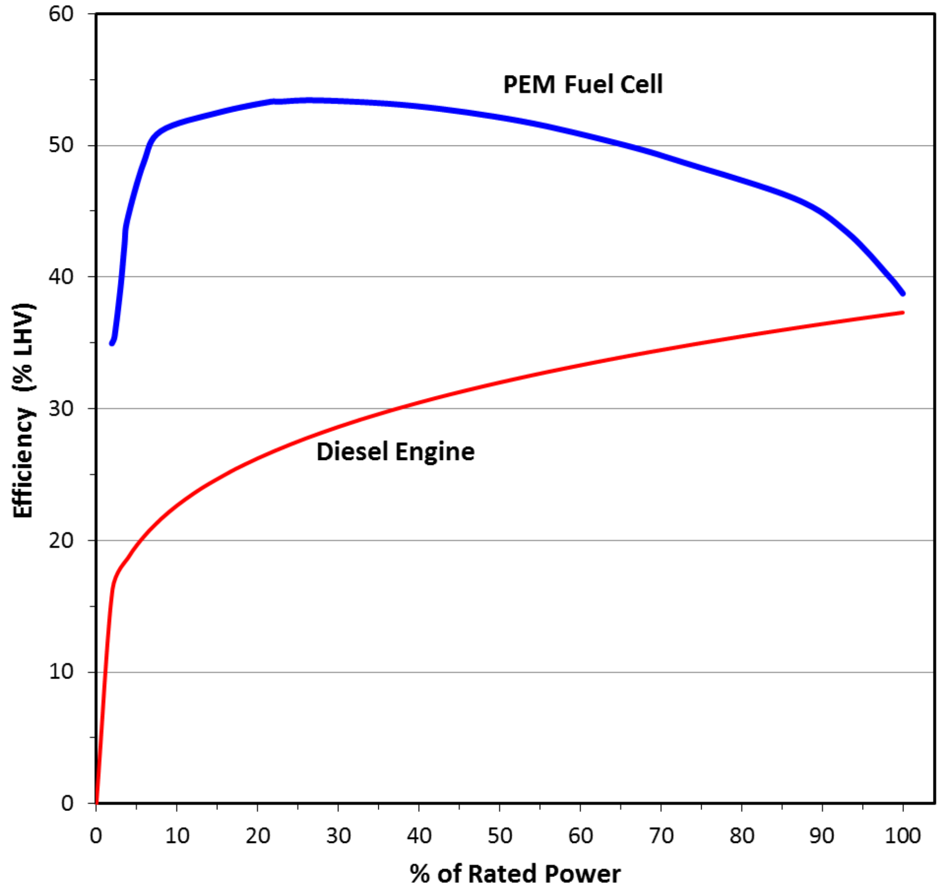

Figure 2: Comparison of efficiency characteristics of hydrogen fuel cells and diesel generators. Hydrogen fuel cell data from manufacturer supplied information for a Hydrogenics HD30 PEM system. Diesel generator data from manufacturer-supplied information for a Perkins 2206D-E13TAG2 (60 Hz) 320 kW and a Cummins Model DFEH Genset, 60 Hz, 350 kW generator, averaged.

Figure 2 illustrates the inherent difference in efficiency characteristics between a diesel generator and a hydrogen fuel cell. It can be seen that fuel cell efficiency increases as load is reduced from 100%, reaching a peak near 25% load. By contrast, diesel engine efficiency continually decreases from 100% load through all part loads.

Low efficiency at part load causes the engines to burn more fuel for the same amount of power. Figure 3 illustrates this by showing the amount of fuel burned per kWhr of energy produced for both diesel engines and fuel cells. It can be seen that the fuel burn of a diesel generator increases as load is reduced, while that for a fuel cell remains relatively constant.

Part load behavior also has an adverse effect on air emissions. Figure 4 shows air emissions for the same diesel generators operated at part load. In all cases, the air emission per kWhr of energy produced becomes worse as load is reduced from its maximum.

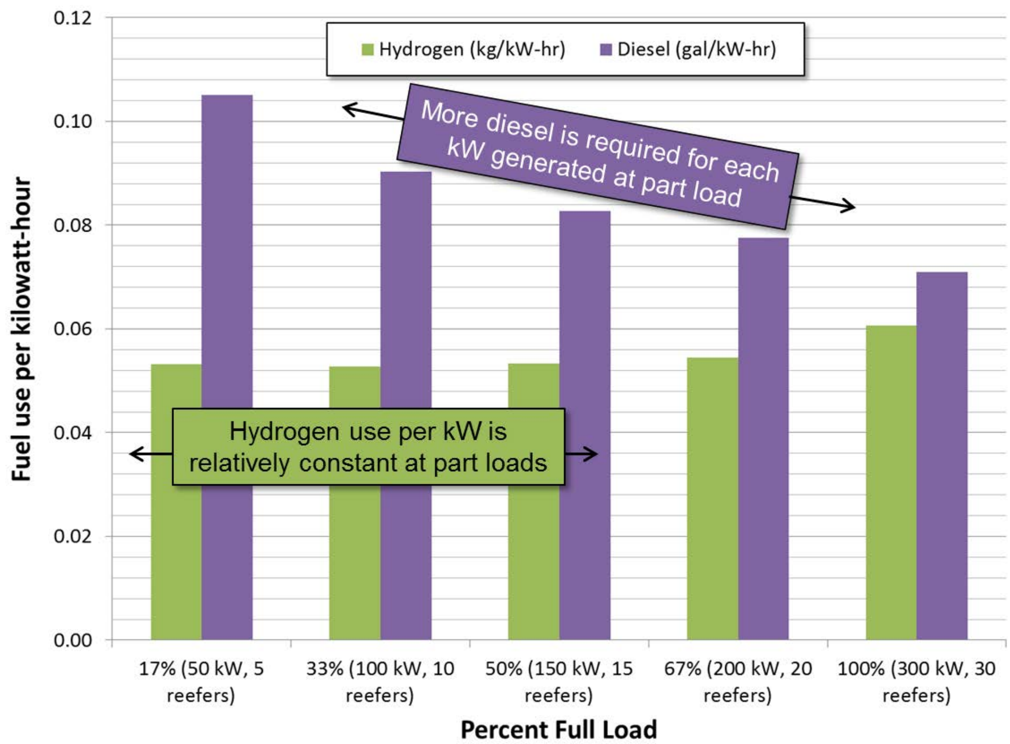

Figure 3: Fuel used per kW-hr of energy produced for diesel engines (purple) and hydrogen fuel cell (green), for varying load demand. Data based on the same information as Figure 2.

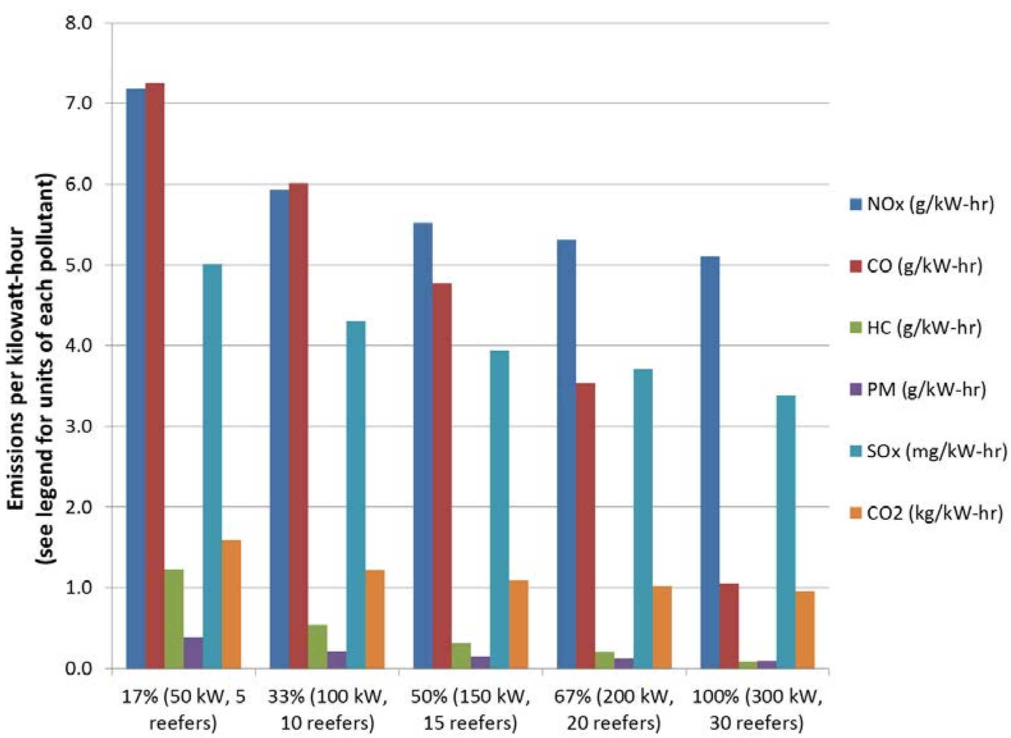

Figure 4: Diesel generator air emissions at part load. Refer to legend for the scale of the Y-axis. Data based on the same information as Figure 2.

The cost of generating power with diesel engines has increased over the last 20 years due to continual tightening of criteria pollutant air emission regulations for diesel engines and stricter fuel cleanliness requirements imposed on diesel fuel. The first emissions standard, Tier 1, was phased in between 1996 and 2000, followed by Tiers 2 and 3 from 2000-2008. The current emissions standard is Tier 4, which was phased in between 2008-2015. Each of the Tier 1-3 steps required modifications to the engine, while Tier 4 requirements can only be met with aftertreatment systems. While EPA estimated a capital cost increase of 1%-3% per engine for meeting the Tiers 2-3 steps and another 1%-3% for meeting the Tier 4 requirement, anecdotal information from manufacturers and customers of diesel engines and equipment show an incremental cost increase of 20%-30% for the transition from Tier 3 to Tier 4, with an accompanying loss of performance and higher maintenance requirements.

There is no reason to expect a change in the trend of increasing criteria pollutant air emission regulations. These requirements on the engines and fuels will be compounded by expected carbon regulations aimed at reducing greenhouse gas emissions at the same time. Hydrogen fuel cells inherently meet all of these regulations due to their zero emission nature. As the cost of diesel power generation is expected to continue to increase due to regulation, the opportunity increases for hydrogen fuel cells to achieve market penetration into these segments.

In summary, replacing diesel generators used primarily at part load with hydrogen fuel cells in a port environment appears to be technically viable while resulting in lower emissions and lower fuel consumption. In addition, there may also be market potential for fuel cell generators in the sizes typically used at ports now and in the future as the cost of diesel power generation increases. For these reasons, there is a need for deployment of a fuel cell replacement for a diesel generator in a port environment to determine the technical and regulatory viability and the commercial value proposition.

2.2 Young Brothers as Initial Deployment Partner

Young Brothers provides water transport of goods between their facility at Piers 39/40 in Honolulu (Figure 5) and ports on the Hawaiian neighbor islands by barge (Figure 6). YB transports perishable and heat-sensitive items in refrigerated containers (“reefers”) which do not have built-in power generators. Instead, while on the dock and on the barge, they plug in to dedicated diesel generators mounted inside mobile 20-foot containers (Figure 7 and Figure 8). Sometimes while on the dock they also plug into the electrical grid where outlets are available.

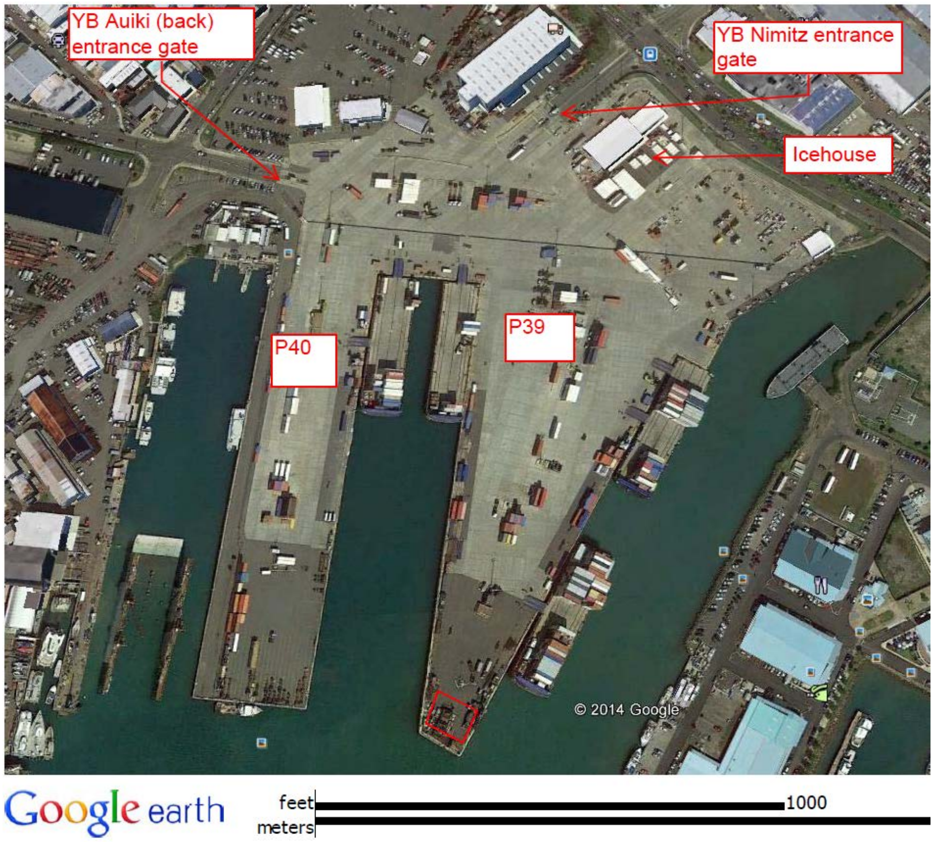

Figure 5: Satellite image of Young Brothers facility in Honolulu.

Figure 6: Young Brothers barge being towed through Honolulu Harbor.

Figure 7: Diesel generator (blue) powering reefers (white) on the dock at Young Brothers' Honolulu facility.

Figure 8: Loaded Young Brothers barge, showing location of diesel generators (yellow stars) and reefers (red triangles).

Observation of YB operations found that although their generators have capability for 30 or more reefers, YB typically only uses each generator for 20 or less reefers. This is because longer cords are required to serve more reefers and the line losses become too large, as well as stacking more than 20 reefers around a single generator becomes logistically challenging. This means that the diesel generators are always operating at part load, and usually no higher than 67%. This is the situation on the dock and on voyages which depart from Honolulu.

The situation on voyages inbound to Honolulu is worse. On these trips, there is usually very little refrigerated cargo. At times the generator may be powering less than five reefers, i.e., operating at less than 20% or even 10% load.

As described in Section 2.1, prolonged part load operation of diesel engines causes maintenance issues, reduces engine life, increases air pollution, and increases fuel consumption. Because fuel cells do not experience these issues, YB became interested in seeing if replacing diesel generators with hydrogen fuel cells could result in ultimate cost savings for their business. An analysis was performed that looked at the fuel cost for six 300 kW generators used to power reefers assuming 1/3 of the time it was operated at each of 33% load, 50% load, and 67% load, using various costs of diesel and hydrogen fuel, and the efficiencies in Figure 2. The results are shown in Figure 9 and reveal that a fuel cost savings can be realized if hydrogen can be obtained for $5/kg or less while diesel costs $4/gallon or more. In the present day, diesel fuel costs are $2.30/gallon, which results in the need for hydrogen to be approximately $3/kg to be cost effective, but the cost of diesel is expected to double in 10 years, reaching $4.69 by 2027 [6]. (If part load behavior is more severe than estimated, the effect on this chart will be to increase the diesel fuel cost while the hydrogen cost would remain nearly constant.)

Based on the potential emissions reduction and fuel cost savings for the operator, Young Brothers agreed to host a six-month deployment of the first containerized hydrogen fuel cell generator made for maritime applications.

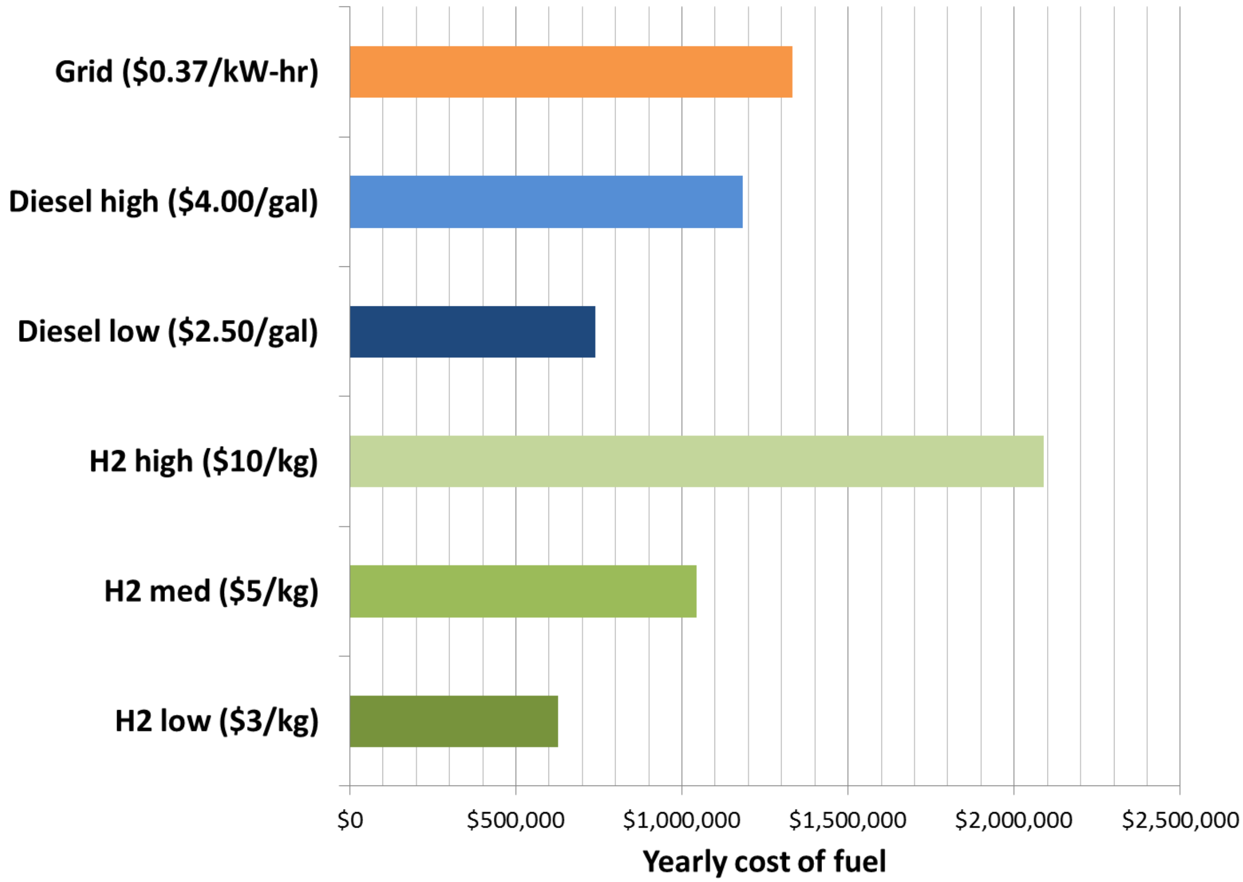

Figure 9: Yearly cost of fuel for running six 300 kW generators in a typical load profile at Young Brothers (33% of the time at 33% load, 33% of the time at 50% load, and 33% of the time at 67% load).

3 Design, Build, and Commissioning

This chapter describes the generator's specifications, design and build process, operating method, and safety features.

3.1 Specifications

The generator specifications were collaboratively determined by the project stakeholders based primarily on two factors: (1) smooth integration into existing operations by being as similar as possible to existing power solution and (2) capabilities of existing hydrogen and fuel cell technologies.

3.1.1 Size and Weight

- 20-foot ISO container basis: 19' 10½" long x 8' 0" wide by 8' 6" tall.
  - High-cube version if possible.
  - 40-foot container is acceptable but not preferred. Will make a final decision during design phase when an assessment of hydrogen storage trade-offs can be made.
- 81,000 lb max gross weight (90% of 90,000 lb (top pick capacity))
- Hydrogen storage section to be an integral part of the overall structure (not removable).

3.1.2 Performance

- ≥ 100 kW continuous power at the plugs
- 240 VAC, 3-phase, Wye configuration
- Ten to twelve 30 Amp plugs
- Capable of operating 10-12 hrs/day on the pier and 28 hr on a barge
- 60-90 kg of hydrogen when stored at 5,000 psi
  - Full power H2 consumption is 8-9 kg/hr → 10 hrs continuous operation if 90 kg stored.
  - Likely will run at partial power during this time as not all reefer units will be requiring full power at all times, so 10-12 hr daily run time is reasonable.
  - To achieve 28 hr, need to average no more than about 35%-40% power during the trip.
- Hybrid battery or capacitor system to handle inrush current (specification determined by reefer power monitoring).

While PEM fuel cells can quickly respond to changes in electricity demand, typical fuel cell power systems use energy storage devices such as capacitors or batteries to ensure the ability of the system to meet electrical load demand changes in the millisecond regime. Determining which energy storage device to use and its size must come from information about the load demand profile. The project team monitored the power consumption of the reefers at YB over a period of two months and found that the reefers have a large number of very short transients during operation (see Figure 10). Using this information the design team at Hydrogenics chose ultracapacitors as the best energy storage device and sized them to handle the short term power spikes appropriately.

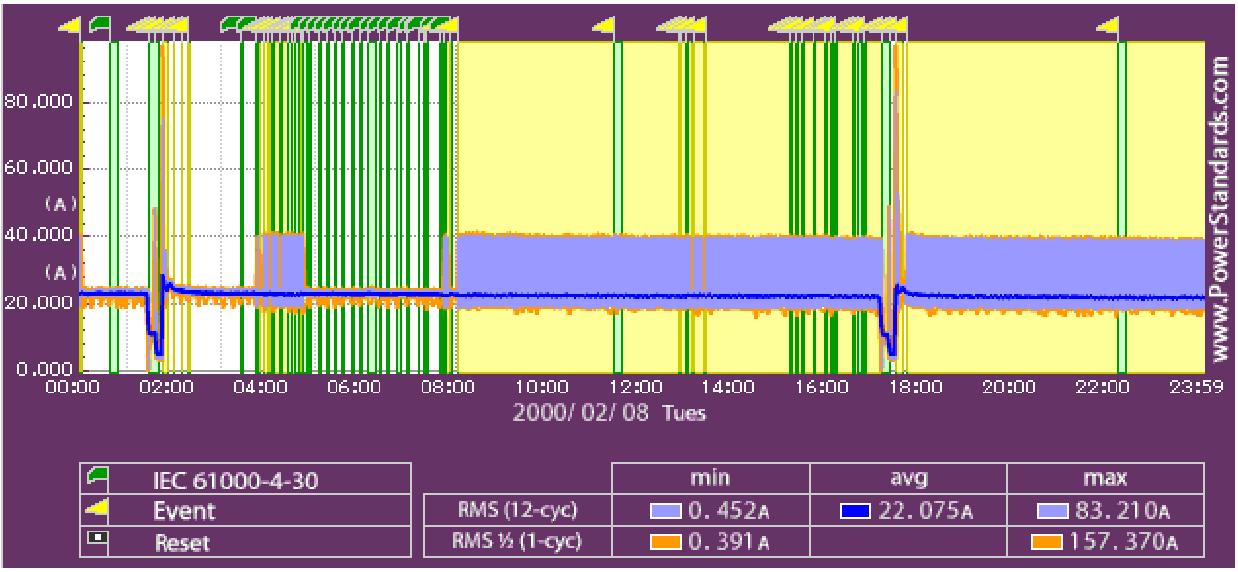

Figure 10: Example of power monitoring data for existing reefers at Young Brothers, used to design the system to meet required electrical load changes. This data shows numerous short-term (< 0.5 s), high-power (4-7 times the average) transients over the course of operation of a 40-foot Carrier Transicold reefer operating at 230 V.

3.1.3 Environmental Conditions

- Ambient temperature +2 to +40 °C
- Tolerate rain, wave wash, salt water intrusion, spray
- Tolerate short-duration (10-20 sec period) side-to-side movement in 18-20' seas.
- Moved around as ordinary container, not operating when moved.
- Fuel cell containing portion in NEMA 3R equivalent enclosure, hydrogen storage portion open to the environment but structurally protected from accidental impact with other machinery.

3.1.4 Codes and Standards

- NRTL inspected (built to applicable requirements).
- USCG and ABS approved for pier-side and barge operation.
- Hydrogen Safety Panel review.
- Local AHJ approval for operation as necessary.

3.2 Design and Build Process

Hydrogenics began designing the generator in early 2014 using the specifications determined above.

In May 2014 a design review meeting was held at the Hydrogenics manufacturing facility in Mississauga, Ontario, and attended by Hydrogenics, ABS, USCG, Sandia, the Hydrogen Safety Panel, YB, Foss, DOE, and MARAD (Figure 11). The design review focused on two aspects: (1) ensuring safe operation and (2) ensuring usability by the end user and identified several areas needing modification or clarification:

Items Needing Modification

- Addition of appropriate louvers and salt/fog filters for maritime/waves
- Indicator light to be in accordance with end-user specs

Items Needing Clarification

- Finalize the valve arrangements on tank manifolds. If transported over the road, what will be required?
- When and where will relief valves vent to, and how will the operator know if the relief valve is open?
- What are the hazardous areas and applicable codes from both land-side and maritime use?
- What are the failure modes for capacitors?
- What is the refueling strategy?
- What is the type of storage tank?
- What kind of damage typically occurs to existing diesel generators ?
- What Nationally Recognized Testing Laboratories (NRTLs) will be used and which codes will they certify to?
- Check whether proposed IEC code for shock and vibration design is consistent with existing maritime code
- Obtain additional reefer run electrical data to ensure appropriate ultracapacitor design
- Check materials compatibility for SS316L in marine environment – chloride stress corrosion
- More detailed P&IDs

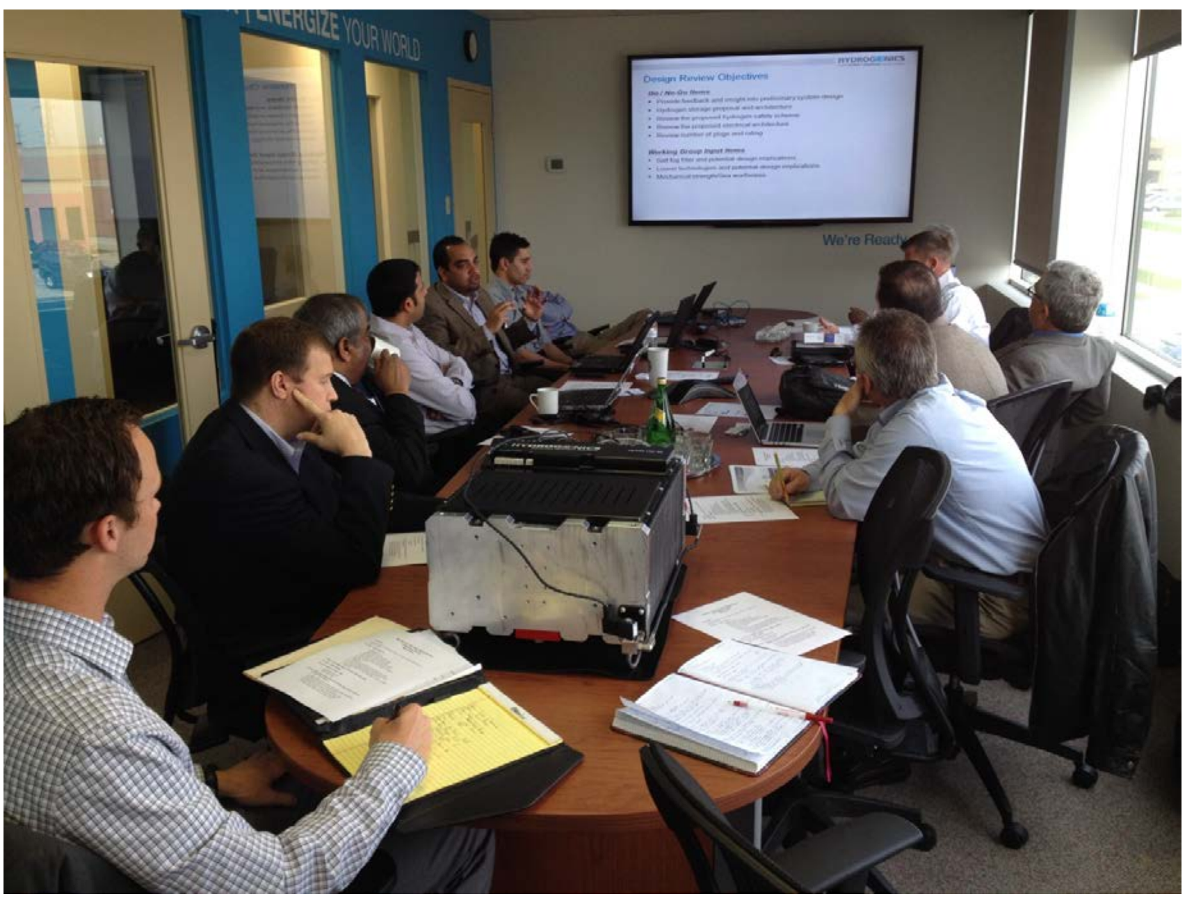

Figure 11: May, 2014 Design Review meeting at Hydrogenics.

In parallel with the design and build efforts, the team achieved resolution on the regulatory requirements. ABS indicated early-on that they would not classify the generator because it is not related to ABS' classed vessel system, but they could classify the container itself if desired by the project team. YB agreed that classification of the container itself is not necessary, but the project team continued to involve ABS review of the design to ensure it meets maritime design standards. At the same time, the project team submitted design documents, largely focused on applicable codes and standards, to USCG to review for approval of over-water operation. The USCG issued a design basis letter in September 2014 stating "general acceptance of the design concept for this particular fuel cell installation" (full letter reproduced in Appendix B).

The Hydrogen Safety Panel's (HSP) involvement in the project as another independent safety advisor dramatically helped in achieving these decisions by the regulators and agreement by the project team. More details on the safety assessment by the HSP and resulting design features of the generator are described in Section 3.4.

The regulatory and safety approvals allowed Hydrogenics to complete detailed design work including air filtration and design for wave splash, appropriate tubing materials, and tank manifolding and control, and they began procuring major components (inverter, hydrogen tanks, etc.). Shock and vibration were assessed by outfitting existing diesel generators at YB with shock monitoring devices. Typical shock was measured less than 2G with only one occurrence between 4G-6G over several months of monitoring. Based on this information, Hydrogenics designed the system to withstand 6G shock loads. The generator incorporates shock monitoring and if a shock greater than 6G is recorded it must be taken out of service and evaluated for damage.

Building of the generator followed two parallel paths: the assembly and testing of individual components and systems, and modification of the container (see Figure 12).

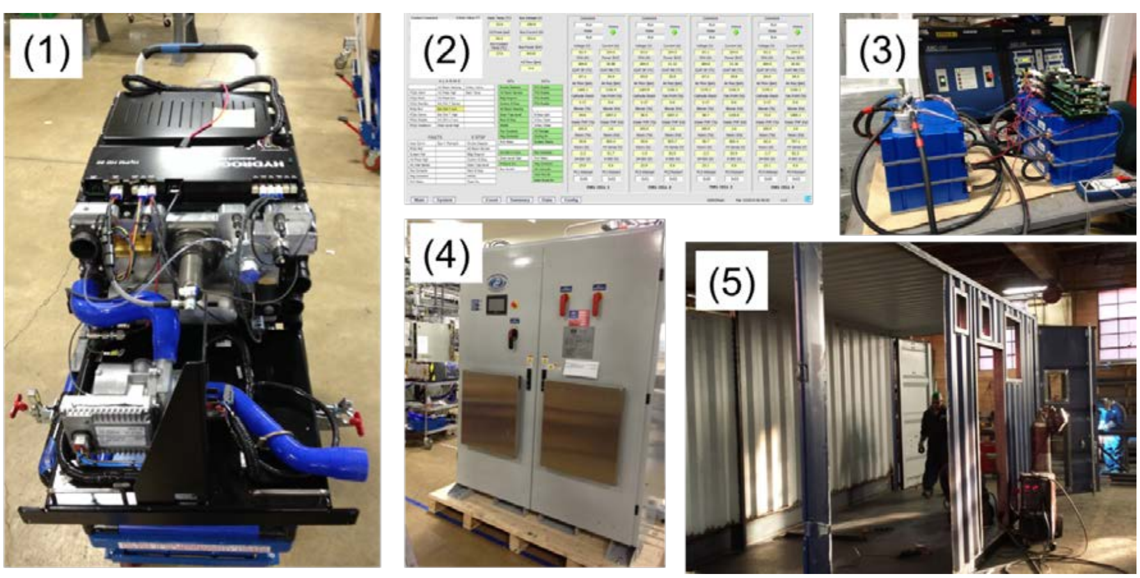

Figure 12: Build progress of subsystems and the container: (1) Fuel cell power module, (2) User interface, (3) Ultracapactitor testing, (4) Custom inverter, (5) Container modification. Photos courtesy of Hydrogenics, used with permission.

Key build milestones included:

- Successful completion of hydrogen storage tank factory certification testing and delivery
- Successful completion of inverter factory testing
- Completion of draft failure mode effects analysis (FMEA), and used it to identify and resolve potential operational handling issues.
- Designed and built hydrogen storage rack and ruggedized fuel cell rack
- Completed fuel cell module assembly
- Finalized procurement for container
- Finalized failure mode effects analysis (FMEA)
- Built and commissioned all four 30 kW fuel cell modules.
- Released detailed container design drawings to subcontractor
- Completed container modifications
- Completed electrical system testing: fuel cell rack + inverter + ultracapacitor

Factory Acceptance Testing was conducted in June, 2015 in two trials. In the first trial, a failed circuit board in the inverter caused the inverter to malfunction, preventing extended run times at moderate loads, and an inverter software bug caused the unit to fail to start up frequently. The inverter manufacturer replaced the defective circuit board and software, and the generator passed the Factory Acceptance Test in late June.

3.3 System Overview

The Maritime Fuel Cell Generator, HyPM-R100kW, is designed and manufactured by Hydrogenics Corp. The system produces up to 100kW of stand-alone, non grid-tied power for marine applications. The generator comprises of a fuel cell power rack, a hydrogen storage system, power-conditioning equipment, controls and monitoring system, and a cooling system built into a standard 20 feet shipping container. Figure 13 shows a schematic of the unit.

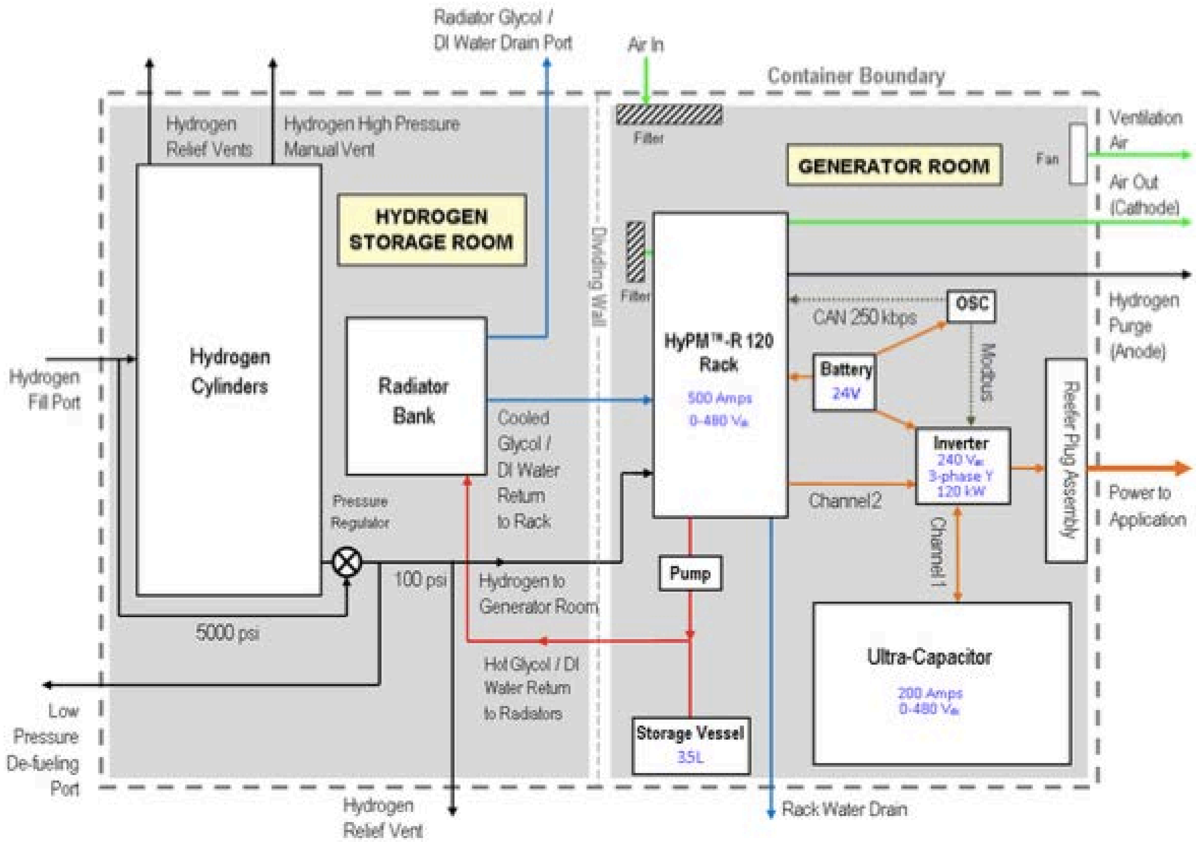

Figure 13. System diagram of fuel cell generator (reproduced from Hydrogenics Corp. with permission from Ref. [7])

Figure 14: The fuel cell generator in its final form. The design has been independently reviewed by the US Coast Guard, the American Bureau of Shipping, and the Hydrogen Safety Panel.

The Fuel Cell Generator is divided into two rooms by a dividing wall: a hydrogen storage room and a generator room. The hydrogen storage room houses 15 composite Type III cylinders that contains up to a total of 75 kg of hydrogen fuel capacity. This room contains other equipment including hydrogen regulators, relief valves, and pressure sensors that monitor hydrogen level safety and decrease hydrogen pressure from a stored pressure of 5000 psi to 100 psi prior to entering the generator room. The hydrogen storage room features a sloped roof design to leverage natural convection for ventilation of hydrogen in the event of a hydrogen leak. Eight additional radiators are mounted below the vent of the storage room and rejects 30kW of heat. The radiator bank consists of 16 fans with a flow rate of 200 to over 1000 cubic feet per minute for cooling purposes.

The generator room houses the fuel cell stack and associated electronics for power production and conditioning. The fuel cell power rack is made up of four 30kW Proton-Exchange Membrane (PEM) fuel cell modules. The room also contains an ultra-capacitor system to meet transient load demands. An inverter converts the DC power produced from the fuel cell and the ultra-capacitor to AC power. Other equipment include a 24V lead-acid (VRLA) battery system for startup, a forced-convection system for air exchange/ventilation purposes, a coolant pump to move the system coolant through the heat exchanger and fuel cell stack, and a control panel to house all the systems controls and monitoring equipment. The room is further equipped with two hydrogen detectors and one smoke detector that are linked to the safety alarm system in the event of a smoke or hydrogen gas detection.

The controls and monitoring system consists of an overall system controller (OSC) to 1) monitor the status of the safety system, including hydrogen and smoke detectors and other components such as the radiators, fans, pumps, valves, etc.; 2) provide controls for solenoid valves, fans, ultra-capacitor voltages;

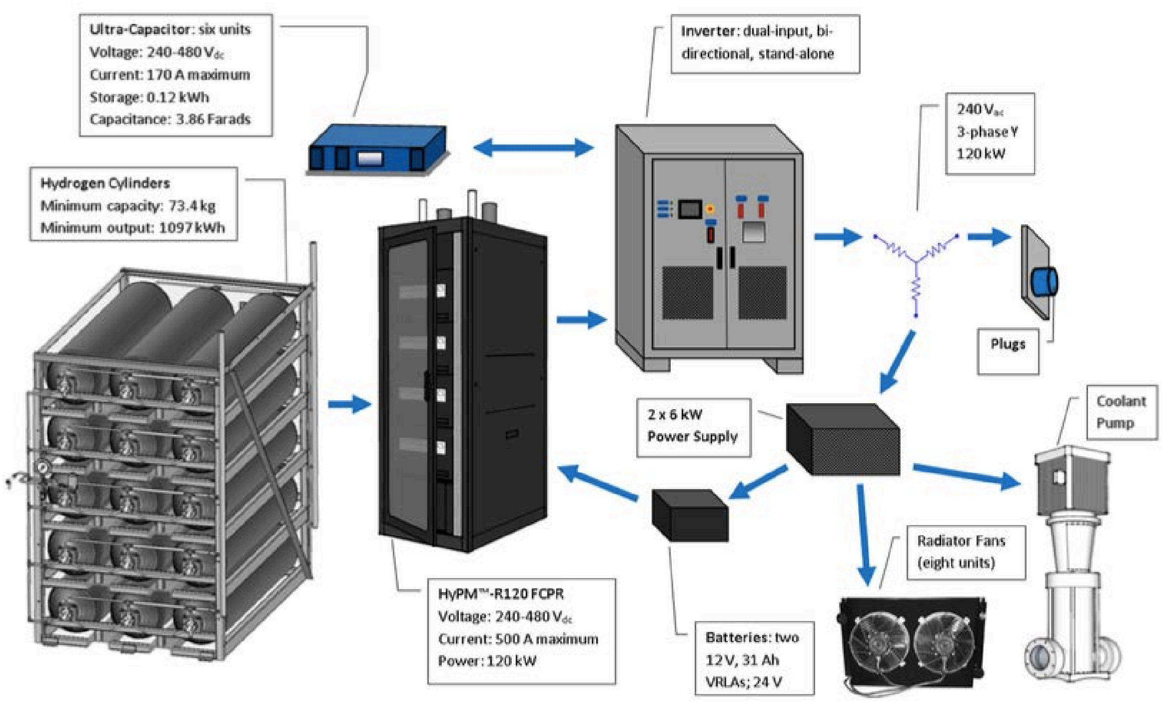

Figure 15. Simplified system process diagram (reproduced from Hydrogenics Corp. with permission from Ref. [7])

and 3) providing communication between the fuel cell power rack and the inverter (the amount of power that the stack is supplying to the inverter). Additionally, the OSC also outputs the main control messages of the system (i.e. Running, Standby or Idle). The Fuel Cell Power Rack (FCPR) controller manages all safety features of the unit. The system is equipped with transmitting equipment (wireless modem and 3G antenna) for data logging and acquisition. Figure 15 shows a simplified diagram of the system process.

3.4 Safety Design Aspects and Reviews

This project used a combination of Failure Modes and Effects Analysis (FMEA) and Quantitative Risk Analysis (QRA) to identify and characterize the risks associated with the prototype fuel cell generator. Hydrogenics led the FMEA portion, which addresses the design and operation of the prototype. Sandia led the QRA analysis, which addresses the use of the prototype within the specific context of the Young Brothers facility.

3.4.1 Design Evaluation

The design of the prototype was examined in two ways. First, the US Coast Guard, the American Bureau of Shipping, and the Hydrogen Safety Panel conducted independent reviews of the design. The Hydrogen Safety Panel determined that the project team "appears to have done a credible job addressing the Panel's comments (apart from those issues still be worked by the project)."[8] The full text of the Hydrogen Safety Panel's comments with the resolution proposed by the project team is given in Appendix A. The US Coast Guard accepted the design concept in a letter to the project lead (in Appendix B). The American Bureau of Shipping did not have any unresolved comments on the design.

Second, Hydrogenics developed the FMEA for the prototype. The significant accident scenarios identified through the FMEA are:

- *Highest consequence* (the failure mode with the potential to result in the worst consequence): Catastrophic failure of the hydrogen storage system if relief valve PRV-02 fails in the closed position.
    - This hazard is mitigated through the use of redundant pressure relief valves on the hydrogen storage tanks.
- *Highest frequency* (the failure mode most likely to occur): Damage to the container floor and slip/trip hazard to personnel if water enters the hydrogen storage room.
    - This hazard is mitigated through use of splash guards, isolation of electrical connections, greasing of mounting points, detection of coolant leaks, periodic inspection of the floor, and use of anti-slip footwear during service.
- *Highest combination* (Risk Priority Number): Puncture of hydrogen tank by a fork from forklift when attempting to handle the prototype leading to uncontrolled discharge and ignition of high pressure hydrogen in the direct vicinity of personnel.
    - It was determined through conversations with the end-user (Young Brothers) that this kind of damage rarely occurs, and if it does, it's in the vicinity of the fork pockets at the bottom of the container as the forklift operator misjudges their location. This failure mode is mitigated by attaching the prototype to a platform and welding the normal fork

pockets closed. When the prototype is moved, the fork pockets on the platform will be used, thus increasing the distance from the new fork pocket to the container by approximately 12". Additionally, the standard container will also be reinforced near the fork pockets with a ¼" steel plate to further reduce the possibility of an accidental fork puncture.

Other notable failure modes from the prototype's FMEA:

- Leaking hydrogen piping and fittings (multiple scenarios) leading to build-up of a flammable mixture within or around the container.
  - This failure mode is mitigated through the use of pressure sensors in the hydrogen piping, hydrogen detectors on the ceiling (one in the hydrogen storage compartment and two in the generator room), the storage room being open to the atmosphere on two sides, the smooth, sloped roof in the generator room to dissipate hydrogen gas to the outside, automatic leak checks on startup and shutdown, minimization of high pressure hydrogen piping, visual shock detection (requiring system check-out before use if shock detected above the design threshold), ventilation in the generator room prior to startup, and a flow-restricting orifice in fuel cell supply piping. The visual shock detection is a key mitigating factor in determining when or if the mechanical shocks associated with the nature of material handling could negatively affect the hydrogen system and the potential for a hydrogen leak.
- Damaged hydrogen tanks due to impact during handling leading to possible high pressure leak.
  - This failure mode is mitigated through procedures which specify the unit shall be taken out of service if it is damaged during handling, which includes denting the walls or dropping it. The unit will then be assessed for any internal damage before placed back into service.

3.4.2 Built-in Mitigation Features of the Generator

As noted above, review by the Hydrogen Safety Panel identified potential improvements in the generator design. These are described in Appendix A.

In addition, the Hydrogenics FMEA results were used to incorporate additional safety features ("engineering controls") into the final design. The main design principles behind these features are:

1. Not allowing accumulation of a hazardous amount of hydrogen.
2. Minimizing stored energy and, when necessary, ensuring releases during normal or emergency operations are non-hazardous.
3. Preventing damage by external events.

A summary of all of the generator's safety features are listed below (with the corresponding design principle(s) referenced above in parenthesis).

- Redundant hydrogen detectors and smoke detectors shut down the entire system and sound a loud audible alarm if a leak or fire is detected. (1)

- Multiple automated hydrogen leak checks which must be passed every time the generator is started, with automatic shutdown (and alarm when necessary) if leaks are detected. (1)
- Hydrogen and smoke detectors can be left on even when the generator is not running. (1)
- Constant forced-air ventilation throughout the generator room with automatic shutdown in case of ventilation failure. (1)
- Automated hydrogen tank valves require power to open and power circuit is hard-wired to emergency stop circuit. Any power failure or emergency stop condition (initiated by the operator or by automatic checks) causes these valves to immediately close. (1)
- Two open sides and a roof slanted to an end-opening in the hydrogen storage area allow for constant passive ventilation and dissipation of any leaks upward. (1,2)
- Fire-wall separation of the high pressure hydrogen storage from the electrical systems in the generator room. (1, 2)
- Five fail-closed valves must be open before hydrogen can reach the fuel cell. (1,2)
- Flow-restricting orifice reduces hydrogen leakage in case of pipe breakage. (1,3)
- Minimized high pressure hydrogen piping, including zero high pressure piping in the generator room. (2)
- Redundant pressure safety devices prevent high pressure from reaching the low pressure piping or the generator room. (2)
- Each hydrogen tank is equipped with two pressure relief devices that open to relieve pressure if a fire is detected, eliminating possibility of tank explosion. (2)
- Electrical ultracapacitor is automatically discharged whenever the unit is turned off. (2)
- High pressure hydrogen releases (due to emergency condition or component failure) are directed upward and away from personnel. (2)
- The only operator interface is on the end of the container opposite the hydrogen storage area. (2)
- The tanks used to store hydrogen are the same used around the world in hydrogen fuel cell cars and buses and built to standards ensuring integrity if impacted. (3)
- Reinforced sides near the fork pockets reduce the chance of a forklift inadvertently piercing the container wall. (3)
- The container’s own fork pockets have been welded closed and the container must be mounted on a platform or handled with a top-pick, further reducing the chance of inadvertent damage by forklift handling (3)

3.5 On-site Commissioning

The generator arrived at Young Brothers’ Honolulu facility on July 24, 2015. On-site commissioning went from August 3-12 according to the schedule described in Table 1. Hands-on Operational Training was also given during this time, which is described more in Section 4.3.1.3. The commissioning process identified several issues, most of which were fixed during commissioning and a few others at a later time. These are divided into three categories and described below.

Table 1: Summary of On-site Commissioning Tasks

Day	Commissioning Tasks	Training
Aug. 3	1. Mechanical Verification: (Visual Inspection of all major systems including the container as indicated in section 5 of the operations manual) 2. Electrical Verification: (24V and sensor checks, all 24V components power on) 3. Cooling system top up: Propylene-Glycol loop. 4. Cooling system top up: DI water loop. 5. Get system ready for transport to be refueled at Hickam: Unscrew Lockouts on tanks, Pull Modem from system so that setup can be worked on outside system.	
Aug. 4	6. Transport system to Hickam for Hydrogen refueling 7. Hydrogen Leak check system while refueling. 8. Modem setup external to system. (ongoing during week) 9. Transport system back to YB for operation with Reefers 10. Positioning of reefers for use with unit (Can be done while unit is out for refueling if possible). 11. Initial runs of system with reefer loads 12. Slowly work way up to maximum number of reefers	
Aug. 5	13. System testing with reefer loads. 14. Touch up any external damage to container.	Detailed training
Aug. 6	15. System testing with reefer loads. 16. Install Corrosion resistant pipe clamps 17. Install Shock Monitors (while pipe clamps are being installed, shock monitors to be installed by YB/Sandia)	
Aug. 7	18. Electrical hardware/software fixes 19. Added internal cooling fans	Overview training Detailed training
Aug. 8	20. Testing with reefers 21. Unit to Hickam for refueling	
Aug. 10	22. Paint roof white 23. Configure interior airflow and ventilation for better cooling 24. Testing with reefers (up to 10)	
Aug. 11	25. Testing with reefers	Overview training Detailed training
Aug. 12	26. Testing with reefers 27. Turnover to YB	

3.5.1 Hardware Issues

1. Exhaust air from FC gets sucked into air inlet. This worsens the room temperature problem. Rotated exhaust louver 90 deg. clockwise to direct the flow away from the air inlet and added a drain because it will allow rain water to enter in this configuration. This also helps alleviate the problem of water dripping from FC exhaust down the doorway which may be a corrosion issue.
2. Room temperature is high, reaches 50 C (122 F) at times (see Figure 16). White/shade has an obvious effect. Painted the roof white, added a fan inside of the air intake filter to boost airflow

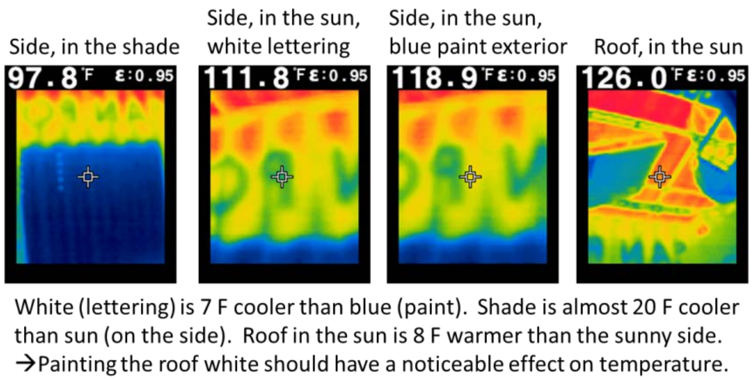

Figure 16: Thermal measurements of the wall temperature at various points in the fuel cell room.

into the unit, and added a fan on top of the inverter directing flow at the fuel cell rack. Assessed operating temperature specifications of each component inside the room to determine acceptability at 50 C ambient, or replacement.

3. DI water use is high. Caused by higher than expected evaporation through the vent in the tank due to the high box temperature. Changed the reservoir to a pressurized system. Mandated daily DI water checks.
4. Smoke detector alarm tripped during hydrogen detection mode, but no smoke or fire observed, and no traces of smoke or fire when the box was inspected. Determined that smoke detector malfunctioned due to continued operation higher than its specified temperature range. Replaced with a device with appropriate maximum operating temperature range.
5. Washing the hydrogen storage room piping with high pressure water may intrude on electrical contacts. Greased all electrical connections to avoid potential water intrusion during wash.
6. Revised the coolant fill method to make it easier to replenish the glycol without introducing air into the system.
7. Changed 24 V circuitry to accommodate additional power required by fans.
8. Removed a damaged diode in the battery charging circuit. If the battery needs to be recharged, if the charger is hooked up in reverse it will damage the charger (no different than any automotive battery).

3.5.2 Software Issues

1. During fill some of the integrated tank fill valves seemed to require more than 30 psi to open, up to 250 psi in one case. This high opening pressure resulted in tank temperature swings in the tanks during fill higher than the fault condition. If the fault is not cleared within 10 minutes the system will time out. Increased the fault threshold.
2. During fill the pressure at the top right corner and bottom left corner were seeing large differentials at the beginning of fill, up to 200 psi. The high differential caused a fault. Increased alarm setpoint to 250 psi
3. During fill the pressure can quickly rise, sometimes nearly instantaneous when the fueling begins after a pause. The pressure rise fault will cause the unit to shut down at 10 min. Increased the fault setpoint.

4. Unresolved: Email notification not working. Problem traced to Verizon not allowing the OSC to communicate with Yahoo or other email service to send the email, likely due to a policy that helps prevent spam emails. Setup dedicated notification computer at Hydrogenics.
5. Water build-up in FC exhaust drain reservoir often reaching high limit switch, likely because of the gravity-drain nature of this system. This causes the unit to fault at the current time limit of the alarm. Changed time limit within the rack from 30 s to 10 min.
6. Coolant pressure drops during long run. At start is about 45+ psi. After long run has decreased to ~35 psi. Further analysis reveals this is not a problem.
7. Inverter high power (7+ reefers) with inductive load was not regulating ultracaps voltage correctly. Software update from inverter manufacturer for better control by the inverter.

3.5.3 Procedural Issues

1. Not clear to operator when to refuel. Marked tank pressure gauge Full, ¾, ½, ¼, and Empty and generated a cheat sheet which relates pressure to remaining run time and number of reefers.
2. Operator needs larger, lower, more permanent operating instructions posted. Printed a decal and posted between the operating panel and plugs.
3. Warm reefers take more continuous power than average during initial cooldown, may not be able to plug in 10 warm reefers all at once. Because this is a total power issue, it is not fixable. Developed a procedure for operating the unit in this situation, e.g., stage warm-box reefer loading.
4. Noise from rad fans is high. Posted hearing protection signage.
5. The controls (including E-stop) are not reachable when the unit is being refueled except by climbing on the truck or a ladder. Since E-stop has little effect while being refueled (and in H2 Detect mode), the station emergency procedure is adopted during refueling.

4 Deployment Preparations

This chapter describes the necessary preparations for deployment of the hydrogen fuel cell generator at the Young Brothers facility. It contains a description of the applicable regulations, site-specific operational safety assessment, employee training, safety reviews and procedures, and emergency response procedures. It also includes operational instructions and procedures for operation and fueling.

4.1 Regulations

As the operator, Young Brothers needed to ensure that the generator would be deployed in a safe manner. Acceptance of the safety of technology is typically accomplished by adherence of the design and operation to applicable codes, regulations, standards, rules, or guidelines. To accomplish this,

Table 2: Summary of regulations, codes, rules, and guidelines examined for applicability to the deployment of the fuel cell generator at Young Brothers dock and on its flat-top, unmanned barges.

Organization	Title	Year	Type	Application	Applicable?
DNV	Rules for classification of Ships/High Speed, Light Craft and Naval Surface Craft; Part 6, Chapter 23: Fuel Cell Installations	2011	Rule	Permanent installation providing power to on-board manned vessels	No
Germanischer Lloyd	Rules for Classification and Construction – VI.3.11 Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats	2003	Guideline	Permanent installation providing power to on-board manned vessels	No
Bureau Veritas	Guidelines for Fuel Cell Systems Onboard Commercial Ships (Guidance Note NI 547 DR R00 E)	2009	Guideline	Permanent installation on-board new manned vessels	No
National Fire Protection Association	NFPA-2: Hydrogen Technologies Code	2011	Code	Land based stationary hydrogen systems	Only to the fueling operation, not to the generator's design or use
US DOT – Federal Motor Carrier Safety Administration	Guidelines for use of Hydrogen Fuel in Commercial Vehicles – Final Report	2007	Guideline	Installed on-board vehicles over public roads	Only during transport over public roads, not during use
US DOT – Pipeline and Hazardous Materials Safety Administration	CFR 49 Sections 100-185	2014	Regulation	Hydrogen carried as cargo	No

existing documentation that has topical relevance to deployment of a hydrogen fuel cell generator in a Port environment and on-board the Young Brothers barges was examined. The results are summarized in Table 2. As can be seen in the last column, none of these documents are applicable the design or operation of the generator in this situation.

In order to provide some basis for safe operation, the project team decided as a first step to construct a theoretical approach based on the prescriptive requirements of these documents, despite their inapplicability. The main focus of the investigation was the setback distances for personnel, equipment, and operations to ensure the safety of personnel in all states of generator operation – normal or abnormal. The end result of blindly applying these prescriptive requirements is shown in the setback distance maps of Figure 17 and Figure 18. These figures have significant, confusing, and ultimately unworkable setback distance requirements for deployment of the generator in the busy port environment at Young Brothers. Based on this feedback, the project team decided to abandon this approach and use an informed, risk-based approach to determine the setback distances. While more labor intensive, the risk-based approach ensures the most appropriate application of safety requirements on the generator's operation. It is described in the next section.

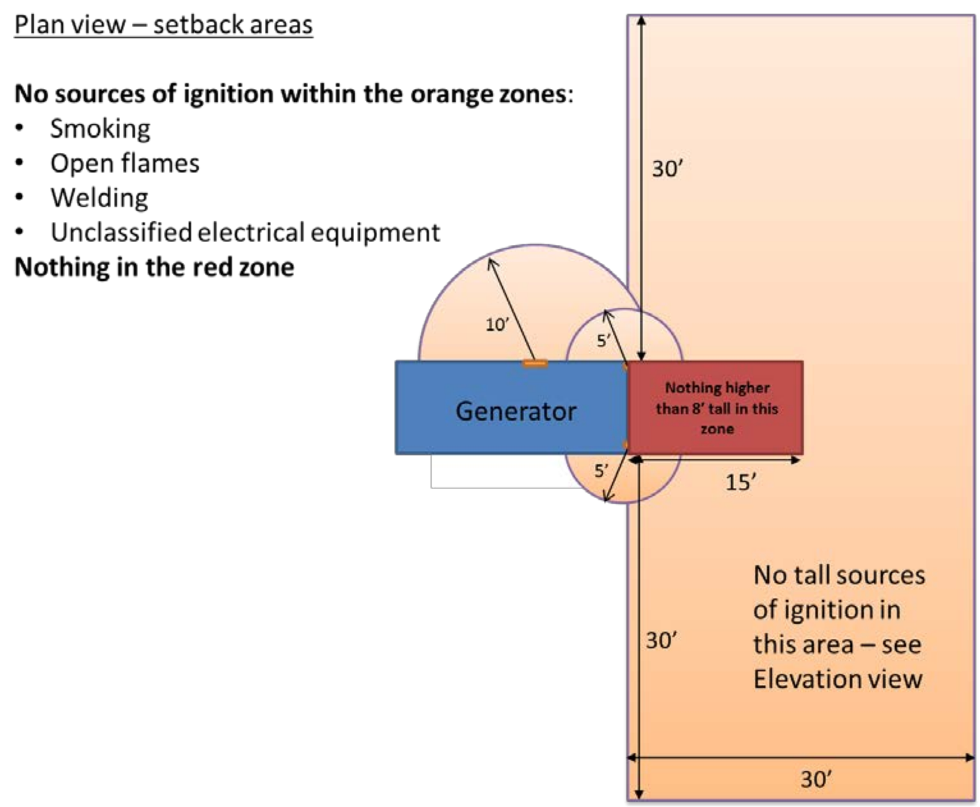

Figure 17: Plan view of the un-workable, theoretical setback distances derived from applying prescriptive requirements in topically-related but inapplicable codes, rules, and recommendations as summarized in Table 2.

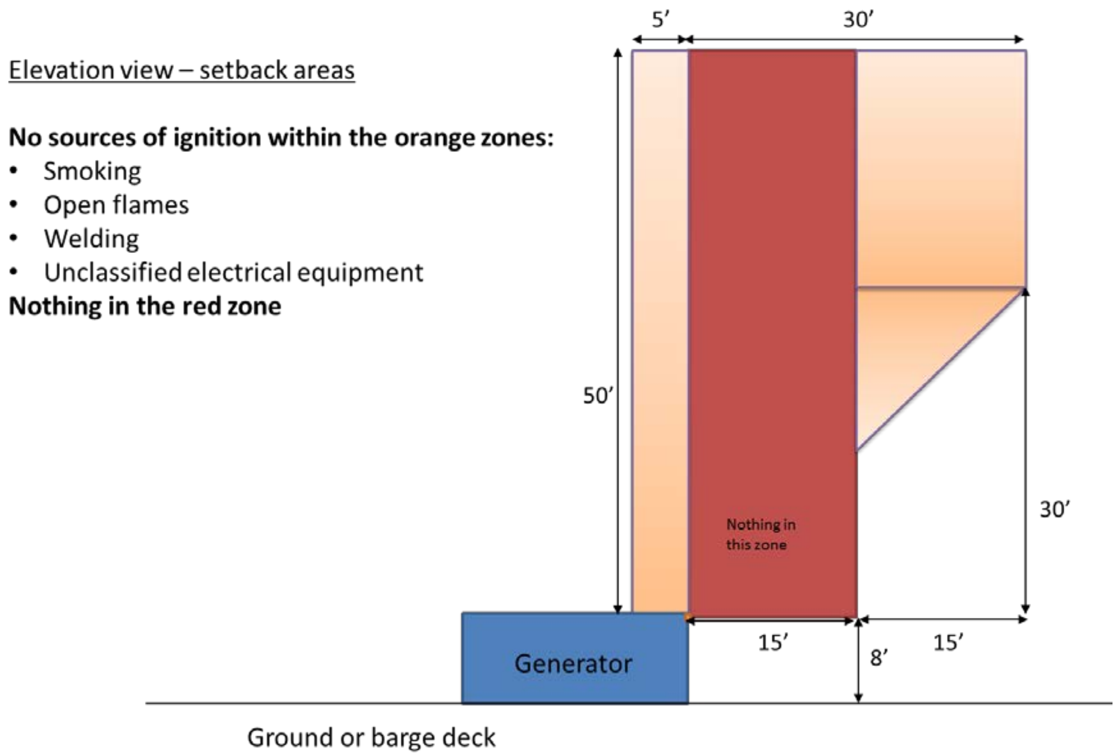

Figure 18: Elevation view of the un-workable, theoretical setback distances derived from applying prescriptive requirements in topically-related but inapplicable codes, rules, and recommendations as summarized in Table 2.

4.2 Site-Specific Safety Analysis

In addition to hazards presented within the prototype generator (described in Section 3.4), the normal operation and failures must be assessed in the context of the operations at Young Brothers facilities. For example, hydrogen leaking or venting out of the prototype will not present a hazard by itself, but if the prototype is near an ignition source then the combination could be hazardous. Therefore the project team performed a site-specific hazard analysis that consists of four parts:

1. Site survey of the Young Brothers normal operations and planned use of the prototype
2. Assessment of the prototype's FMEA and operation states to determine operating or emergency scenarios most likely to present a hazard within the context of the Young Brothers operations.
3. Fluid dynamics simulations of hydrogen releases into the environment to assess the distribution and extent of flammable hydrogen concentrations.
4. Quantitative Risk Assessment to quantify the risk to personnel associated with the hydrogen system and a comparison to industry-standard risk numbers for comparative presentation to the project team.

On different occasions, Hydrogenics' project team members and a Sandia risk assessment expert visited Young Brothers' dockside and marine operations facilities to perform site surveys and characterize current operational methods by observing day-to-day operations (on-dock, on-barge, and tug operations) and meeting with Young Brothers' safety and operations managers (Figure 19).

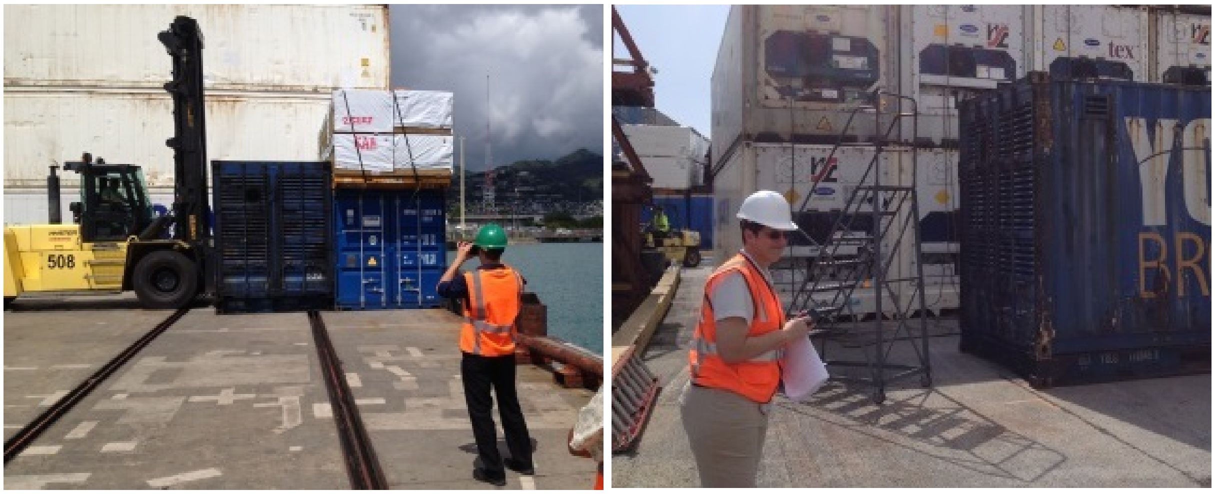

Figure 19: On different occasions, Hydrogenics' project manager Nader Zaag (left) and Sandia risk analysis expert Dr. Chris LaFleur (right) observed Young Brothers' operations first-hand to identify potential safety concerns.

4.2.1 Generator Design Recommendations

During the Hydrogenics site survey, the team identified two areas of potential concern:

1. Damage to the generator by forklift handling
2. Blockage of the generator's ventilation systems by adjacent containers.

Figure 20 shows some damage observed on existing diesel generators. Damage can occur by impacting the forklift's load carriage or backrest extension, or by impacting the edge of an adjacent container when lowered into place. Damage can also occur if an adjacent container being placed impacts the generator. In subsequent discussions the damage was characterized by Young Brothers maintenance personnel as:

> *The dents [shown in Figure 20] average 2" to 6" [deep]. Frequency would be for every 100 times the container is handled 30 of those times will result in some form of damage. Fork damage is usually in the lower portion of the sidewall and to the fork pockets and frames themselves.*

In response to these observations, Hydrogenics revised the design to remove mounting of equipment and piping on the side walls and to provide additional space between them and the wall. In addition, two handling-specific safety features were added to the design: reinforcement around the fork pockets and mounting the generator on a platform, which effectively increases the distance between the normal location of the forklift fork and the prototype side wall.

Figure 20: This existing diesel generator showed evidence of damage because of forklift mis-handling. Damage can occur by impacting the forklift's load carriage or backrest extension, or by impacting the edge of an adjacent container when lowered into place. Damage can also occur if an adjacent container being placed impacts the generator.

Hydrogenics also observed that the shock a container experiences when handling seemed to be more of an issue than the vibration. To help quantify this, Sandia and Young Brothers outfitted an existing diesel generator with simple shock monitors and found that most shocks during normal use on the dock and on the barge were under 2G, but there was one instance where the shock registered between 4G and 6G. Based on these observations, Hydrogenics ruggedized its hydrogen storage tank frame and its fuel cell rack frame to withstand at least 6G shock. The prototype will be outfitted with shock monitors during its on-site commissioning period and operating procedures will require inspection if shock greater than 6G is indicated.

To understand what physical situation might lead to a shock greater than 6G, Sandia estimated the shock loads that a container would experience if completely dropped, see Table 3. The table shows, for example, that if the impact from a 1-foot drop is assumed to last for a duration of 0.5 seconds, the unit will experience a 4.9 G shock.

Table 3: Shock (in G-loads) resulting from various drop scenarios

Impact duration	Drop Height					
	6 inches	**1 foot**	**3 feet**	**6 feet**	**12 feet**	**20 feet**
0.25 s	6.9 G	9.8 G	17 G	24 G	34 G	44 G
0.5 s	3.5 G	4.9 G	8.5 G	12 G	17 G	22 G
1 s	1.7 G	2.4 G	4.2 G	6.0 G	8.5 G	11 G

Red numbers indicate values higher than the 6G design.

These design changes have mitigated the safety risks of forklift handling; however, Hydrogenics still recommends handling the generator with a top-pick to reduce the chance of damage and resulting downtime and repair cost.

The second potential concern raised during the Hydrogenics site visit is a blocked ventilation system by stacking the generator directly adjacent to another container, a common practice with current diesel generators when loaded on the barges (see Figure 21). This will prevent active ventilation of the generator room and will also prevent air from reaching the fuel cell. The system will automatically shut-down if either of these occur thus mitigating any safety hazard, but will result in loss of power to any connected refrigerated containers. Hydrogenics' specifications require two feet of separation between the side of the generator with the vents and any adjacent container or structure during operation. To assist handlers with identification of this need, the vents are identified with highly-visible, "safety yellow" lettering (see Figure 22).

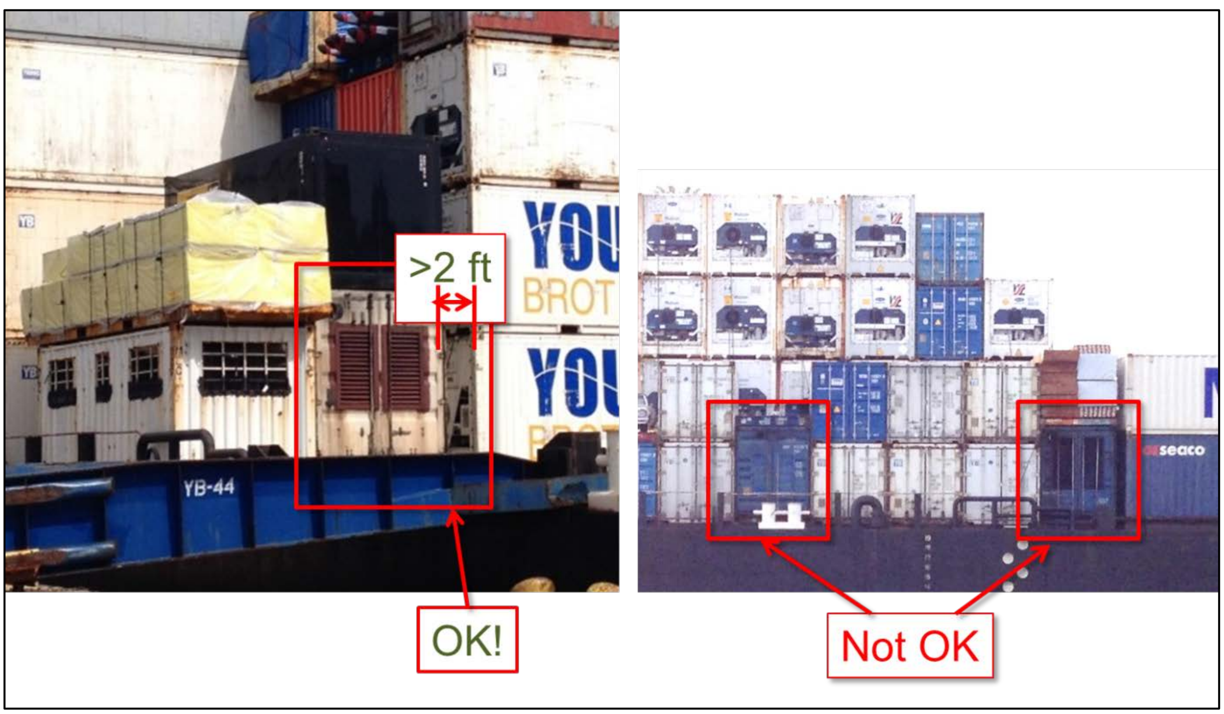

Figure 21: Typical placement configuration of existing diesel generators on the barges leave little or no room along the container walls.

Figure 22: Yellow markings above vents indicate openings not to be blocked.

4.2.2 Generator Usage Recommendations

During the Sandia risk assessment site survey, Young Brothers staff explained that the prototype will be used in one of four operational states:

A. In idle storage on the pier away from normal activities.
B. Parked on the pier, in use or awaiting use, in areas of the pier where refrigerated containers are staged prior to loading and after unloading.
C. Parked on the barge prior to sailing, underway and after reaching the destination pier.
D. In transit between the parking areas, being maneuvered by the material handling fork trucks or top picks.

Each of these states and locations was reviewed and compared to failure modes and hazard scenarios identified in the FMEA to identify scenarios of concern that needed to be further characterized to evaluate the risks. The results of the site-specific hazard analysis and review of the FMEA identified one scenario for further analysis. This scenario was identified to be if a thermal or pressure relief valve fails open, exhausting hydrogen out the relief vent lines as a jet into the atmosphere.

4.2.2.1 Hydrogen Release Characterization

This hydrogen release scenario described above has three possible outcomes: 1) the hydrogen release does not encounter an ignition source, rises rapidly due to its inherent buoyancy and vents harmlessly into the atmosphere, 2) the hydrogen release does not ignite immediately and builds up into a combustible concentration due to a confinement of some sort and eventually meets an ignition source resulting in an explosion, or 3) the hydrogen release ignites immediately due to friction/static discharge or the presence of another ignition source and results in a hydrogen jet flame.

The first outcome is harmless. The second outcome was deemed not feasible because no usage scenario observed at Young Brothers would result in an accumulation of hydrogen in a confined space that could result in a delayed ignition and explosion. Justification for this conclusion is discussed below. The only possibility where confined space explosion may occur would be if the prototype vented in an area with a ceiling structure, but this was not simulated because it was not observed at Young Brothers.

The third outcome, a jet flame, may result in property damage if the jet were to impinge on nearby equipment, or result in an injury if personnel are located in the immediate vicinity. If needed, Young Brothers has agreed to modify their standard operations to accommodate special placement of the prototype and/or surrounding equipment in order to avoid likely scenarios of injury or unacceptable property damage.

In order to determine which modifications may be necessary, the hydrogen release scenarios were modeled using computer simulations that characterize the size and extent of the resulting hydrogen jet. Figure 23 shows that a hydrogen jet exiting the relief vent (and flame, if ignited) will likely be a maximum 14 meters long (horizontal) at the beginning of the hydrogen venting, when the pressure in the system is greatest. After 10 seconds of venting however, this jet is reduced to 8 meters. The entire contents of a venting hydrogen cylinder will be expended within 2 minutes. Note that the orientation of the relief vent is 45 degrees above horizontal which determines the direction of the jet. In addition, the vent location is approximately 10 feet above the ground. This height and upward orientation combined with the very high buoyancy of hydrogen result in no observed usage scenario at Young Brothers where

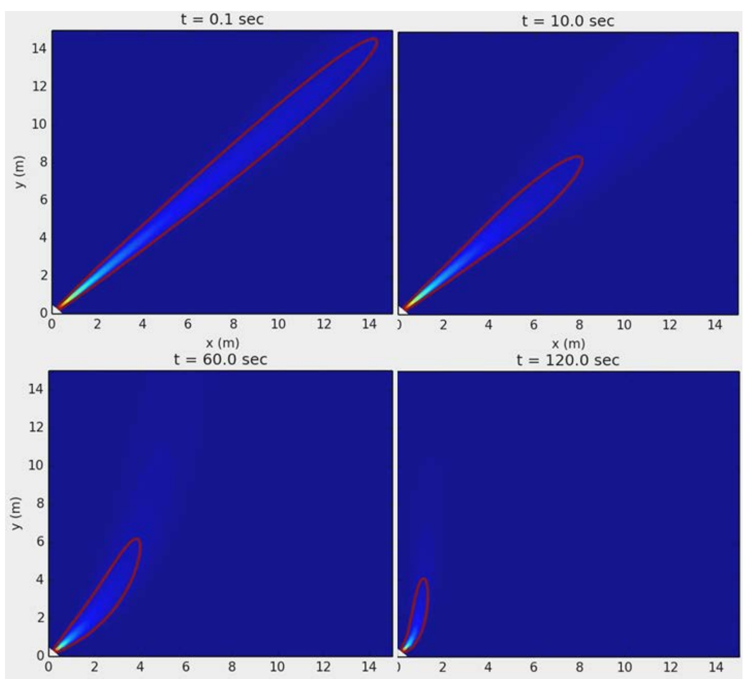

Figure 23: Time-lapse results from computer simulation showing the extent of released hydrogen in the case of a thermal or pressure relief valve opening with full pressure (5,000 psi) inside the storage tanks. The red outline indicates the boundary of the 4% molar concentration of hydrogen. If an ignition source is within the red outline it is possible, but not certain, that the hydrogen will ignite.

the hydrogen ignition could result in a confined space type of explosion. This applies even in the case of containers surrounding the prototype on all four sides.

Table 4 shows the results of probability calculations based on empirical failure data of components within the prototype[2]. From this table it can be seen that the only expected outcome that could result in personal injury is a jet flame. A release leading to a jet flame that has potential for personal injury has a probability of occurrence of 0.000957, or less than once in every five years of continuous operation.

It is important to distinguish that this is the probability of a jet flame that can cause injury, not the likelihood of actual injury. The likelihood of actual injury combines the probability of the jet flame with that of the person being in a location where they could be harmed by the jet flame. To help determine locations where someone could be harmed, the effect of the direct and radiant heat of the fire is examined. Figure 24 shows the temperature distribution within a jet flame out to 8 m. Someone within the zone of the flame itself would be burned in a very short time. However, the figure shows that the flame itself is confined to a relatively narrow area with a maximum radius of 0.5 m (20 inches) from the center.

Table 4: Probability modeling results which show that the only expected outcome that could result in personal injury is the jet flame following a full release of hydrogen. The probability of a release causing a jet flame that has potential for personal injury is 0.000957, or about once in every five years of continuous operation.

Scenario	End State	Probability (Average events per year)	Contribution to PLL[a]
0.01pct Release	No Ignition	0.65369087	0.00%
0.1pct Release	No Ignition	0.11390703	0.00%
1pct Release	No Ignition	0.04529515	0.00%
10pct Release	No Ignition	0.02346609	0.00%
100pct Release	No Ignition	0.01865201	0.00%
0.01pct Release	Jet fire	0.00236179	0.00 %
10pct Release	Jet fire	0.00120451	0.00 %
100pct Release	Jet fire	0.00095740	100.00 %
10pct Release	Explosion	0.00058109	0.00 %
100pct Release	Explosion	0.00046188	0.00 %
0.1pct Release	Jet fire	0.00041155	0.00 %
1pct Release	Jet fire	0.00016365	0.00 %
0.1pct Release	Explosion	0.00000000	0.00 %
0.01pct Release	Explosion	0.00000000	0.00 %
1pct Release	Explosion	0.00000000	0.00 %

[a] PLL: Potential Loss of Life

[2] These probabilities were developed in a separate project and involved statistical analysis of generic leak probabilities and available hydrogen data from many sources. A full description of the method used is presented in Ref. [9].

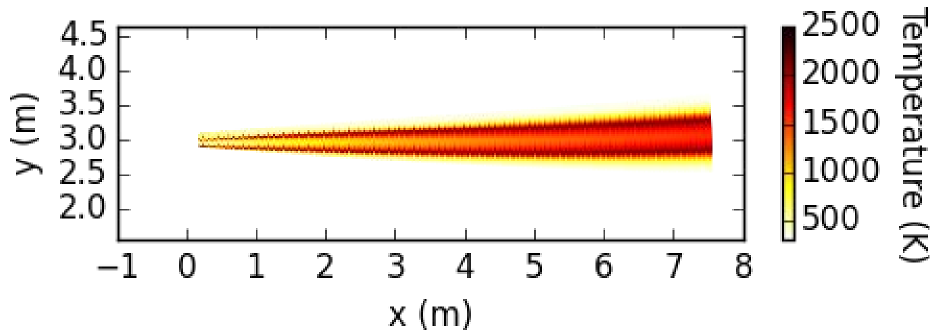

Figure 24: Temperature distribution of the hydrogen jet flame modeled. The flame boundary is relatively narrow, with a 20 inch radius at its maximum point.

Injury can also result from radiant heat, that is, exposure to the heat of the flame without being in the actual flame zone. Figure 25 shows the heat radiation (heat flux) resulting from the same jet flame. In this plot the flame goes from right to left, with the red horizontal arrow in the middle showing the centerline of the flame. There are three boundaries shown in the plot: boundary 1 is the smallest, teardrop-shaped green-colored zone; boundary 2 is a larger, light blue nearly-spherical zone; boundary 3 is the largest, blue squat cylinder. These boundaries correspond to the 2012 International Fire Code (IFC) exposure limits for property lines (1.577 kW/m^2), employees (4.732 kW/m^2), and non-combustible equipment (25.237 kW/m^2). Boundary 2 is the relevant one for this assessment since it is determined based on an allowable exposure to employees.[10] The radius of boundary 2 varies from approximately 2.7 m (9 ft) at the beginning of the flame to approximately 4.1 m (13 ft) at the widest portion.

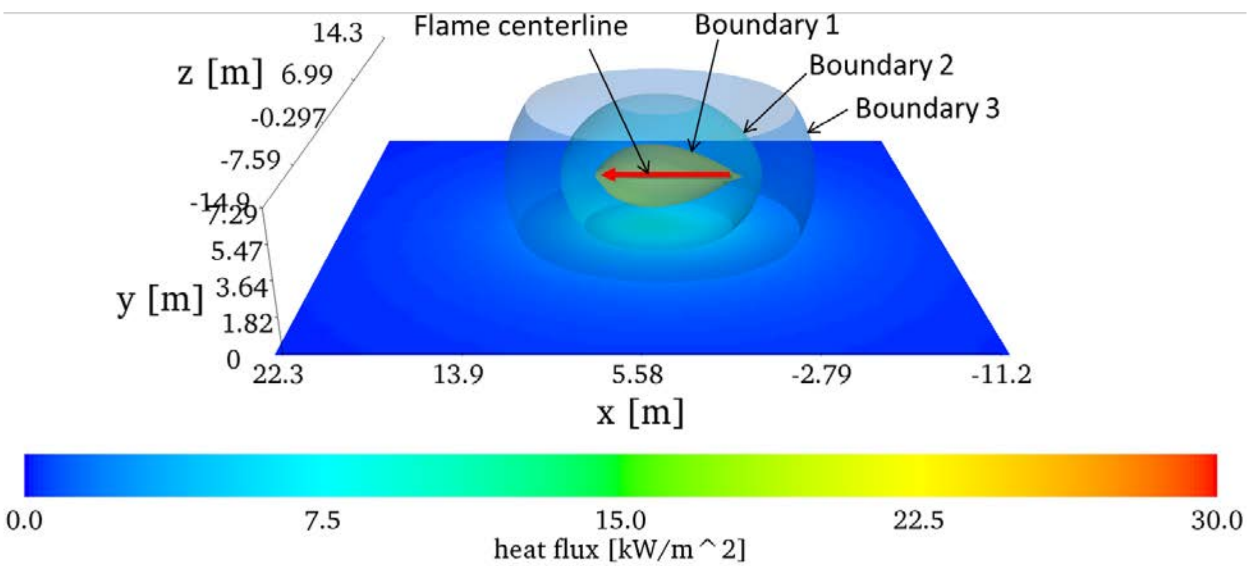

Figure 25: Radiation heat flux from the jet flame modeled in this analysis. Boundary 2 corresponds to exposure limits for employees according to the 2012 International Fire Code.

In summary, these results show that:

1. The probability of a release event leading to potential injury is approximately equivalent to less than one time in five years of continuous operation.
2. This release event is a full-scale release resulting in a jet flame.
3. Examination of the flame temperature and heat flux plots reveal that exposure with potential for injury to employees can occur within 9-14 feet of the centerline of the jet, assuming the person stays within this zone for at least 30 seconds.

4.2.2.2 Site Recommendations to Minimize Impact of Potential Hydrogen Release

Based on these results a "zone of potential hydrogen release" is established along the centerline of the projected jet with a diameter of 10 feet (see Figure 26 and Figure 27) and the following administrative controls are recommended:

1. If workers need to enter the zone of potential hydrogen release they should transit it as quickly as possible. If that is not possible then the generator should be re-oriented until the worker is clear. The reason for this control is related to the 30 second exposure time limit. It is assumed that normally aware and physically capable workers will immediately remove themselves from the zone of potential hydrogen release should a release occur. Work in this zone should not be permitted because (a) it can distract the worker from being aware of a release, potentially prolonging their exposure and (b) during work in this zone, if a worker becomes incapacitated and a release occurs, they will not be able to remove themselves from this zone and may be exposed for a duration that can cause injury.

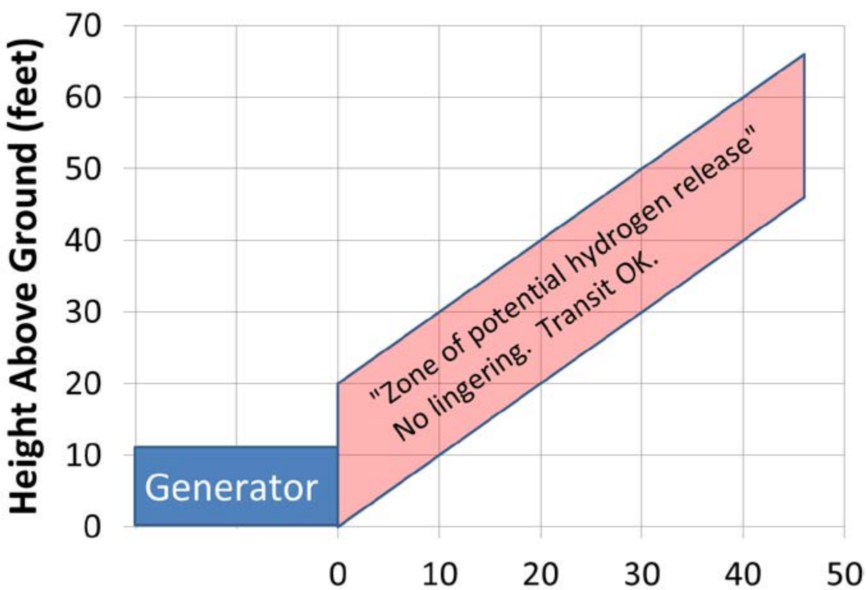

Figure 26: A zone of potential hydrogen release is proposed based on flow and flame modeling combined with release probability assessment. Workers can transit the zone but should not work in it. In case of fire in or around the prototype generator, the zone should be avoided.

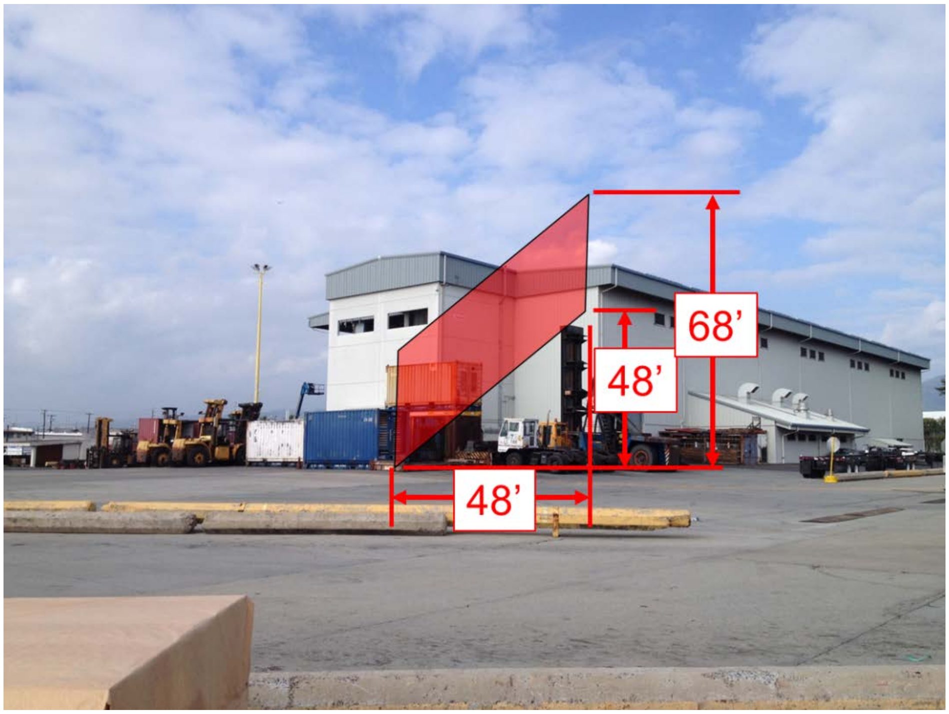

Figure 27: Young Brothers facility showing an example of how the zone of potential hydrogen release would be applied (using an existing containerized diesel generator, blue, as a surrogate for the prototype).

2. In case of a fire in or around the generator do not enter the zone of potential hydrogen release. The thermal pressure relief devices on the hydrogen tanks are designed to release the hydrogen in the tanks if a fire is sensed. Release and jet fire should be expected in this case.

The risk analysis also looked at the case (Operational Scenario C) where the prototype is placed on the barge with the vent end pointing towards the water, and an assist tug boat coming alongside. The zone of potential hydrogen release also applies in this case. The relative heights of the prototype on the barge and the tug in the water (see Figure 28), combined with the tug's position forward or aft of usual generator placement, makes it unlikely that any appreciable portion of the tug would be in the zone of potential hydrogen release for any amount of time needed for exposure.

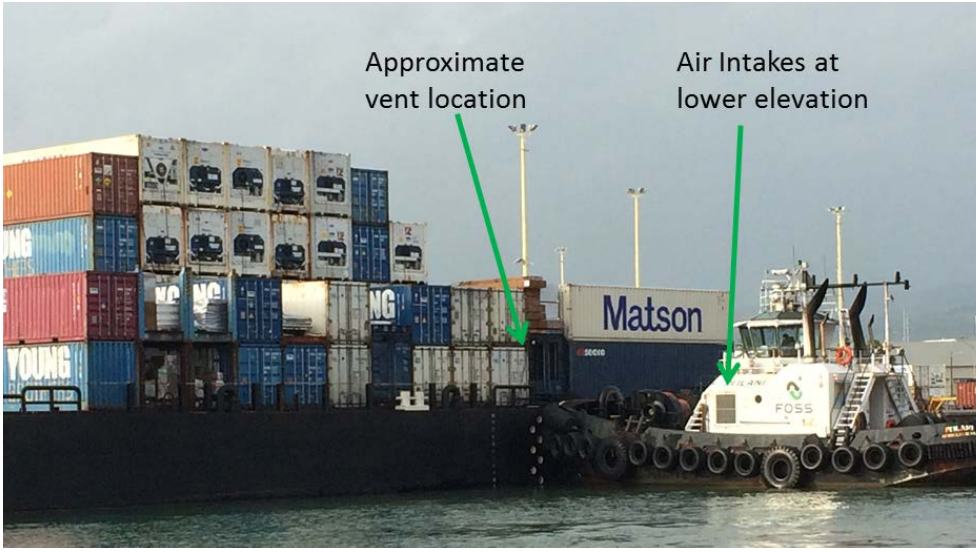

Figure 28: Assist tug boat and intakes relative to relief vent height of the prototype on the barge. Based on release modeling results and observations of tug-barge interactions there does not appear to be a scenario that could cause a hazardous condition on the tug boat.

Another concern about a tug alongside the prototype during a release was the potential for unignited hydrogen to be sucked into the interior spaces on the tug boat or into combustion air intakes for the diesel engines. Figure 28 shows that the air intakes on the assist tug are located at a lower elevation that the hydrogen relief vent approximate location. Given the plume modeling results, hydrogen's buoyancy property, and the horizontal distance between the barge and the tug boat intakes, this scenario was also deemed not feasible to cause a hazardous condition on the tug boat.

Young Brothers staff requested the analysis team to consider the effect of high relative humidity (common in Hawaii) on the results. Changing relative humidity will slightly change the water content of the air, which in turn can affect the density and heat capacity, which are two important factors in the release modeling work. Two scenarios were examined:

1. Low water content: 10 °C, 40% RH. Water content = 0.2% H_2O by mole
2. High water content: 30 °C, 95% RH. Water content = 1.5% H_2O by mole

The difference in water content between these two scenarios is just over 1%. The resulting effect on density and heat capacity is negligible and well within the uncertainty in the preceding modeling results. In other words, humidity changes will not affect the results.

This analysis and discussion has resulted in establishment of a "zone of potential hydrogen release" and corresponding administrative controls. It is recognized that despite these precautions, there is still a chance that injury can occur. Using site-specific operation information, the overall risk of this prototype causing injury to personnel was quantified using a hydrogen-specific quantitative risk assessment model [11, 12] and the Fatal Accident Rate (FAR) for overall use of this prototype was found to be 0.89 fatalities in 1,000 50-year worker careers (100 million exposed worker hours) if the conservative 30 second exposure is assumed. When these results are compared to available data from the Bureau of Labor

Table 5: Comparative values of occupational risk, including that calculated for the prototype, for occupations similar to those observed at Young Brothers. From US Department of Labor Bureau of Labor Statistics, Ref. [13].

Industry	FAR per 100 million exposed hours[a]
Truck transportation	11.6
Driver/sales workers and truck drivers	11.5
Industrial machinery installation, repair, and maintenance workers	10.4
Support activities for transportation	5.1
Electricians	4.2
First-line supervisors/managers of mechanics, installers, and repairers	3.3
Laborers and freight, stock, and material movers, hand	3.1
Industrial truck and tractor operators	3.0
Warehousing and storage	2.6
First-line supervisors/managers of production and operating workers	2.5
U.S. Workforce total	1.8
Fire fighters	1.6
Management, business, and financial operations occupations	1.3
Prototype (calculated)	**0.89**
Office and administrative support occupations	0.20

[a] BLS statistics are presented in the original source as FAR per *200* million worker hours and have been halved for presentation here to compare directly to that typically used in risk assessments and calculated for the prototype.

Statistics Census of Fatal Occupational Injuries [13][3] for occupations similar to those observed at Young Brothers, shown in Table 5, the risks represented by the hydrogen system are shown to be similar to the occupational risk of office workers, and less than 10-times the occupational risk of some observed occupations such as truck drivers and machinery workers. This indicates that the risk presented by the hydrogen system is much less than the risk exposure of all transportation and warehousing occupations in general. When the administrative control of allowing only transit through the zone of potential hydrogen release is implemented (minimizing the chance of any worker being exposed for 30 seconds or more), the FAR is expected to be lower still.

4.3 Safety Efforts

4.3.1 Employee Training

Several different safety and operational training sessions were conducted before and after the generator arrived at Young Brothers. Prior to generator arrival, the project team conducted hydrogen familiarity and firefighting training to prepare first responders. This built on the hands-on firefighting training of nearly 300 Honolulu and Hilo firefighters conducted in 2013 around hydrogen vehicles as part of a different project. Following that, Young Brothers held internal training sessions leveraging the resources established by the project team. When the generator arrived on-site in August, 2015, both

[3] Injury rate statistics compiled by BLS are on a 200 million worker hour basis and have been halved for incorporation into Table 5.

Hydrogenics and Sandia held hands-on operational training for appropriate personnel. The YB Safety team is tracking training records for everyone. Any Machine Operator (MO) or other employee who has not received this training will not be allowed to move or operate the generator.

These trainings are described in more detail in the following sections.

4.3.1.1 Pre-Deployment: Hydrogen and Fuel Cells Familiarity and Emergency Response Training

In April 2015, the project team provided hydrogen familiarity training for the personnel who will be in contact with the prototype unit during normal business operations, and firefighting training for those who may be called upon in case of a hydrogen fire. The training was organized and administered by Pacific Northwest National Laboratory (PNNL) as an adaptation of their "National Hydrogen and Fuel Cell Emergency Response Training" program previously developed with funding from the US Department of Energy's Office of Fuel Cell Technology. The National training program focuses largely on hydrogen fuel cell-powered light duty private and commercial vehicles and stationary facilities, and has been presented to first responder organizations throughout the states of California, Hawaii, and Washington. The training was adapted to the application at Young Brothers and also enhanced with a demonstration of a hydrogen burner, provided by Paul Ponthieux of Blue Planet Research. The final report from PNNL regarding the April on-site training is included as Appendix D.

Training was conducted in 12 sessions over six days; morning and afternoon sessions on April 9-10-11 at Young Brothers Honolulu facility and similar sessions on April 15-16-17 at the Maui Fire Department's training facility in Kahului. A total of 226 people attended the combined training sessions. Of those, 164 were first responders from Honolulu Fire Department and Maui Fire Department. Seven were at-sea responders from Clean Islands Council. The remainder was comprised of workers from Young Brothers, the local US Coast Guard, and various other local hydrogen stakeholders.

The training session on April 10 was video recorded by Searider Productions, a student elective activity at Wai'anae High School in Honolulu, HI. Working with the project team, Searider produced two versions of the training video – a full, unedited version (1 hour 11 minutes) and a shorter version (50 minutes) intended for those with a more operational focus. The full length version is publically available on PNNL's "H2 Tools" website[4]. The shorter version was subsequently used by Young Brothers staff to train personnel who could not attend the April training in person.

A "Safety Features" fact sheet was produced in conjunction with the training sessions and given to all attendees. The fact sheet summarizes the implemented design safety features and operational safety controls to ensure safety of all personnel involved in the project. This is included in Attachment D of Appendix D.

[4] https://h2tools.org/content/maritime-fuel-cell-project-and-hydrogen-safety-training

Figure 29: Hydrogen awareness and emergency response safety training session at Young Brothers on April 10, 2015.

The training sessions produced a variety of questions. To make answers available to all attendees and for future training efforts, Sandia produced a "Frequently Asked Questions" which focuses on many common safety questions about the design and use of the generator. This is included as Appendix C.

4.3.1.2 Pre-Deployment: Training of Young Brothers Personnel

In late July, 2015, Young Brothers conducted an internal training campaign on hydrogen awareness and safety. This training utilized the shortened video from the April training session as well as a background presentation of the project. This resulted in an additional 85 Young Brothers Honolulu-based personnel who received the awareness training (in addition to the 11 present at the April sessions) for a total of 96 trained personnel.

In late August, 2015, Sandia and Young Brothers conducted awareness training of 30 Young Brothers personnel at Kahului, Maui. This training included the shortened video, Q&A, and a demonstration of hydrogen production via electrolysis and hydrogen sensing.

4.3.1.3 Post-Deployment: Operational Training of Young Brothers Personnel

The generator arrived and was commissioned in Honolulu from August 2-12, 2015. During the commissioning period, Hydrogenics and Sandia held hands-on operational training for the personnel who would be using the generator on a daily basis. 22 Young Brothers personnel including those from maintenance, operators, and stevedores received the hands-on operational training.

Figure 30: Hydrogenics Project Manager and engineer Nader Zaag (left) giving hands-on training to Young Brothers maintenance personnel during on-site commissioning in August, 2015.

Two types of hands-on training were given: overview training and detailed training. The overview training was meant for any YB personnel on the dock in order to give general familiarity with the generator how to perform basic operating and emergency tasks. The main topics of the Overview training were:

a) System walkaround
b) Normal system usage
c) Indicator lights
d) Abnormal indications and procedures
e) Handling
f) YB Specific Procedures

The detailed training session include the Overview training as well as additional information and was intended for those who will have daily responsibility for operation and maintenance of the generator (see Figure 30). Its main topic areas were:

a) How it Works
    i) Hydrogen storage room
        (1) Hydrogen tanks
        (2) Hydrogen filling
        (3) Hydrogen supply line
        (4) Cooling system
        (5) Hydrogen detection
        (6) Sloped ceiling
        (7) Barrier wall and passthroughs
    ii) Generator room
        (1) Fuel cell rack

    (2) Fuel cell modules
    (3) Cooling water system
    (4) Hydrogen detectors
    (5) Electrical cabinet
    (6) Inverter
    (7) Room air

a) Checkout, Maintenance, and Troubleshooting
  i) Operational Check-out Procedures
    (1) Weekly check (during Phase 1); After every voyage (during Phase 2)
    (2) Monthly check (any phase)
    (3) Quarterly check (any phase)
  ii) How to Perform Maintenance
    (1) Fluid checks/top-offs
    (2) DI cooling water beads
    (3) Hydrogen sensors
    (4) Air filters
  iii) Troubleshooting
    (1) Computer interface
    (2) Alarm and Fault email notifications
    (3) Hydrogenics support

4.3.1.4 Training Summary

A summary of training is summarized in Table 6. A total of 14 training sessions occurred during deployment period. These include sessions on project overview, hydrogen safety and awareness, and generator operation.

4.3.2 Safety Reviews

The pre-deployment reviews of the safety aspects of the generator design and operation are extensively discussed in Sections 3.4 and 4.2, respectively.

During the deployment, safety review is an ongoing activity. Every week the generator is used it undergoes a checkout, examining for any problems inside and out and results are logged in the MarFC Generator Periodic Checkout Log (attached in Appendix E). During usage, any hazardous condition or emergency stop is to be noted in the MarFC Generator Daily Usage Log (Appendix F) and immediately communicated to both Sandia and Hydrogenics.

If a safety incident or near-miss occurs, they are recorded on Young Brothers' Incident Report form (Appendix G) or Near Miss & Hazard Observation Report (Appendix H).

In addition to the constant checkouts and logs, monthly usage phone calls with Young Brothers operations supervisors, Sandia, and Hydrogenics are provided as a forum to discuss any safety concerns and to answer questions.

Table 6. Summary of training

Date	Training Name	Description	Number of Attendees
4/9/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	67
4/10/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	58
4/11/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	42
4/15/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	25
4/16/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	17
4/17/15	Hydrogen Safety and Emergency Response Training	Hydrogen safety training	16
7/20/15	General Awareness Video	Safety training to YB employees	8
7/21/15	General Awareness Video	Safety training to YB employees	51
7/22/15	General Awareness Video	Safety training to YB employees	20
7/24/15	General Awareness Video	Safety training to YB employees	14
7/27/15	General Awareness Video	Safety training to YB employees	3
8/4/15	Operational Training	On site training on generator operations for YB employees	18
8/7/15	Operational Training	On site training on generator operations for YB employees	3
8/26/15	General Awareness Video	Safety training to YB-Kahului personnel	30

4.3.3 Safety Events and Lessons Learned

Any safety event would have been logged and the cause of the event to be investigated to obtain lessons learned. Throughout the Young Brothers deployment there were no safety events with the generator or the fueling.

4.3.4 Emergency Response

Emergency response planning began years before the deployment began with DOE and HNEI holding first responder training for hydrogen vehicles in 2013 on Honolulu and the Big Island. A subsequent training for Honolulu and Maui fire departments was given in conjunction with this project in April 2015 as described in Section 4.3.1.1. With both of these efforts, the first responders are well equipped to handle hydrogen emergencies at both ports and at sea.

Emergency response training for Young Brothers personnel focused on two aspects. First is identification of an emergency condition, and second is proper action in case an emergency condition arises. Emergency conditions were identified as:

1. Smoke or fire in or around the unit (different from vapor from the exhaust vent during operation, which is normal)
2. Loud hissing/whooshing noise
3. Severe damage or impact
4. Hydrogen detection horn sounding

The following are NOT emergencies but should be investigated:

1. Reefers not getting power
2. Coolant leaking onto the ground
3. Fluids leaking on the ground when not in use
4. Squealing or grinding noises
5. Fails to start, no indicator lights
6. Significant container damage or holes

Young Brothers personnel were advised to NOT try to diagnose of the cause of the emergency condition nor deal with the consequences (such as firefighting). Rather Young Brothers personnel were advised to notify appropriate first responders to deal with the situation. The communication procedure established is to notify the following entities in order:

1. Local fire department (or USCG if at sea)
2. Young Brothers supervisor
3. Hydrogenics (the manufacturer)
4. Sandia National Laboratories

4.4 Operational Procedures

There are three areas of operation in the project:

1. Operation of the prototype itself (on/off, emergency procedures)
2. Handling and use of the prototype (around the dock, on the barge)
3. Hydrogen delivery and refueling

Each area is described below.

4.4.1 Prototype Operation

The operation of the prototype itself is thoroughly described in the Operation and Maintenance Manual prepared by Hydrogenics. It includes procedures for normal startup and shutdown, emergency shutdown, and a description of conditions that will lead to automatic safety shutdown. It also includes a section on potential hazards and safety precautions. Hands-on training of operators was given by the manufacturer during on-site commissioning and a hard copy of the manual is kept at Young Brothers.

4.4.2 Prototype Handling and Usage

Young Brothers has well-established procedures for handling containerized generators; see the Job Safety Analysis for generator handling in Appendix I. The guiding principle for this project has always been to have as little difference as possible in the handling of the hydrogen fuel cell prototype. The differences in handling were previously described in the Site Specific Safety Analysis section (Section 4.2). Briefly, those are:

- Handling with a top-pick rather than a forklift when possible
- When handling with a forklift, only lift from one side (the non-door side)
- Maintain 2 feet clearance from adjacent containers on the ventilation (door) side
- No work in the “zone of potential hydrogen release”
- No entering the “zone of potential hydrogen release” if there is a fire in or around the prototype.

4.4.3 Hydrogen Delivery and Refueling

The Young Brothers site does not have hydrogen generation or storage facilities. The closest source of hydrogen that is sufficient to meet the large demand of the prototype (up to 70 kg/day) is located at Joint Base Pearl Harbor Hickam (“Hickam”) at a station that is operated by the Hawaii Center for Advanced Transportation Technologies (HCATT). This project has two available methods for hydrogen refueling of the prototype:

- Transportation of the prototype to Hickam for direct fill from the existing commercial dispenser.
- Use a hydrogen delivery trailer to transport hydrogen from Hickam to Young Brothers and fill the prototype on-site from the trailer.

These operating procedures of these two options are discussed in this section.

4.4.3.1 Direct Fill at Hickam

When the generator is ready to be refilled, Young Brothers places it on a chassis (a trailer frame designed to transport shipping containers and pulled by a Class 8 tractor) and call for pickup through a contracted, licensed and certified trucking company. The trucking company transports the generator over public roads to Hickam, approximately 7 miles away from Young Brothers (Figure 31 left).

At the filling station the prototype is not be removed from the chassis. The prototype is filled using the established Hickam procedures for filling vehicles from its 350 bar commercial dispensing nozzle (Figure 31 right). The fills are be attended by a trained technician to ensure safety through maintaining proper fill rate and maximum allowable pressure.

After filling, which lasts 20-30 minutes, the trucking company moves it back to Young Brothers. Young Brothers takes the prototype off the chassis and move it to a location to be ready for the next use. The fill logistics are determined by Young Brothers to suit the usage needs. The Hickam station is normally attended from 0830 to 1530, M-F, although accommodations can be made for refueling outside of these hours.

Figure 31: Left: The generator being transported to the hydrogen fueling station at Hickam Air Force Base. Right: The generator being filled with hydrogen.

During project review by the Hydrogen Safety Panel, Panel members were uncertain whether the prototype would be allowed to transit on public roads utilizing NGV-certified tanks, and recommended the project team to get clarification from US DOT (full Hydrogen Safety Panel prototype review comments are given in Appendix A). The project team developed the following approach, and it was agreed to by US DOT Federal Motor Carrier Safety Administration [14]:[5]

- The design and operation of the prototype is considered to be comparable to that of a commercial fuel cell vehicle and not of a hydrogen storage system. The only reason for the prototype system to store hydrogen is for its immediate use, not for transfer to any another system, and its only interface to other hydrogen equipment is for refueling purposes; same as with a fuel cell vehicle. In effect, it is a "fuel cell bus without wheels" that can be trailered or carried to a location to conduct refueling operations.[6]
- This is consistent with the fact that NFPA 2, which governs hydrogen storage systems, specifically excludes "onboard vehicle or mobile equipment components or systems, including the onboard GH2 or LH2 fuel supply." In other words, NFPA 2 also considers mobile equipment such as this to be functionally equivalent to vehicles and not subject to the same regulations as those which govern dedicated hydrogen storage systems.[7]

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[5] The approach described here is specific to the Maritime Fuel Cell Generator project. The original wording of the approach is not modified here in order to provide accurate information regarding this project, but some clarifications have been added in accompanying footnotes reflecting new information obtained since the deployment. Blind applicability of this approach to other applications or projects is not being recommended or implied.

[6] Since the design of this project's approach, there have been additional interactions between the Hydrogen Safety Panel and the U.S. DOT that indicate a shift towards treating this self-contained generator as cargo. If this new approach is adopted, compliance with the Hazardous Materials transport regulations of the US DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) may be necessary. Until the establishment of a regulation or interpretation specifically governing self-contained hydrogen fuel cell generators or other equipment, consultation with US DOT and the Hydrogen Safety Panel is recommended for guidance on future projects.

[7] The second sentence of this bullet point, which was an attempt to translate the NFPA 2 language to this generator, contains an extrapolation of NFPA 2's intent and should be considered inaccurate. NFPA 2 is not stating

- To meet US DOT requirements for any time when the prototype will be transported over the road, the prototype will be designed to meet the "Guidelines for use of hydrogen fuel in commercial vehicles" published by DOT in November 2007.
- Compressed gas tanks designed, built, and tested according to NGV-2 meet the requirements of the aforementioned guidelines (Section 3.1.1, paragraph 4) and are appropriate for this piece of equipment.[8]

4.4.3.2 Hydrogen Delivery Trailer for Fill at Young Brothers

While not ultimately utilized on this project, the team explored opportunities for delivering hydrogen at the Young Brothers facility and fueling the generator on the dock. At Young Brothers, an area was designated for the filling of the prototype at the end of Pier 39 (see Figure 32). This location was chosen because it is available space that is not typically used for operations, and placement of the trailer here will comply with NFPA 2 (2011) setback distances for hydrogen storage systems.

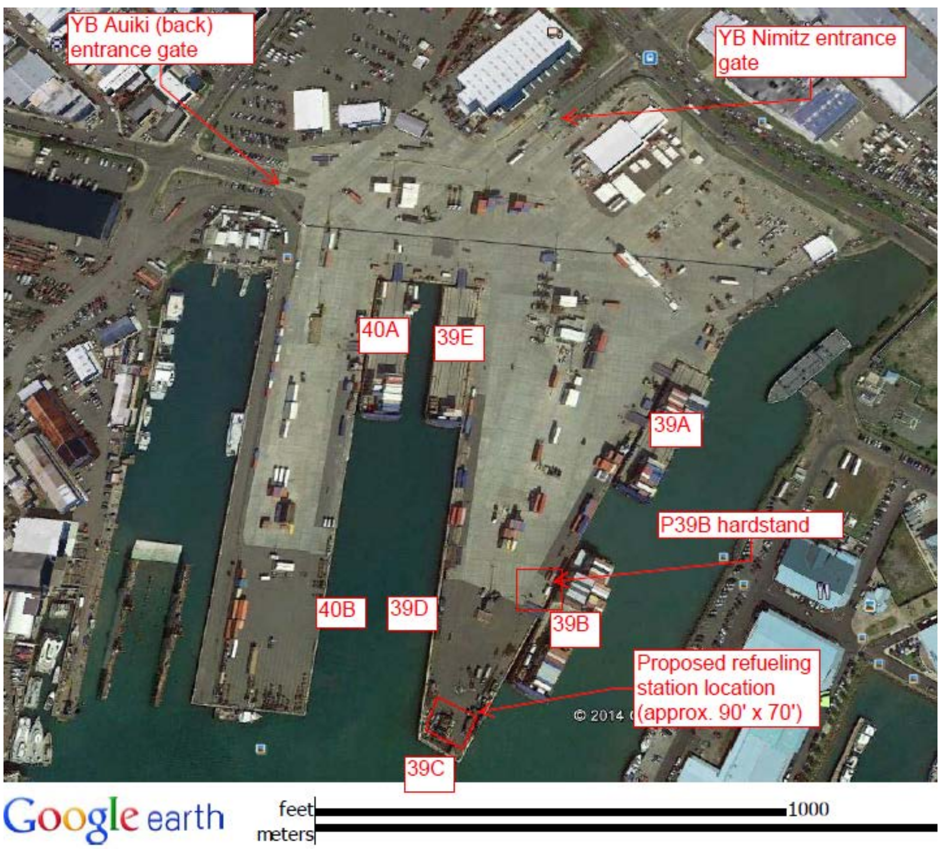

Figure 32: Overhead layout of the Young Brothers' facility. The designated refueling area is shown at the bottom, at the tip of Pier 39.

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that equipment such as mobile APUs are the same as vehicles, only that NFPA 2's requirements do not specifically address them. NFPA 2 does not govern over-the-road transportation of hydrogen fuels.

[8] To clarify this bullet it should read: "The tanks within the Maritime Fuel Cell Generator have been built to the NGV-2 requirements and certified for hydrogen service. NGV-2 certified tanks meet the functional requirements of storage cylinders within the aforementioned guidelines (Section 3.1.1, paragraph 4) and are therefore appropriate for this piece of equipment."

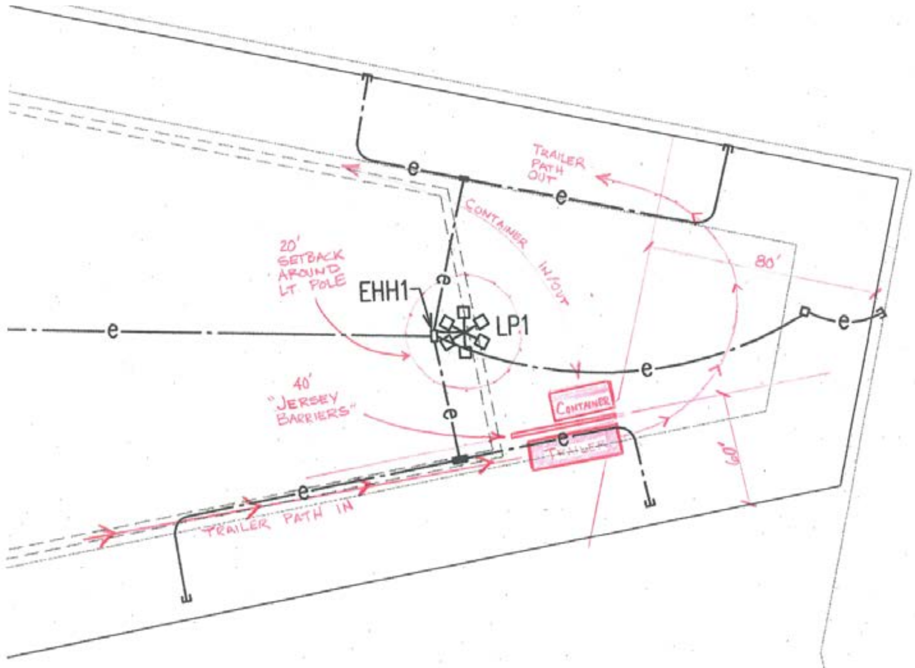

Figure 33: Layout and traffic flow of the planned hydrogen refueling area at the end of Young Brothers' Pier 39.

Figure 33 shows the planned layout and traffic flow for both the generator and the trailer. A trained technician would be used to perform each fill of the prototype and would follow a set procedure designed with safety as the foremost objective.

Filling at Young Brothers requires hydrogen to be delivered to the site from the Hickam station. Hydrogen delivery would be done with a commercially-produced transport trailer. A cascade-type fill would be simplest and not require any power for the process (as opposed to a fill that requires a compressor). A trailer with a correct combination of hydrogen quantity and pressure to cascade into the generator and result in a 100% full state (75 kg at 5,000 psig) would need to be engineered and built. One example trailer that could accomplish this is one that holds ~240 kg hydrogen at 5,500 psig in thirty 320 L tanks and cascades three tanks at a time. Other combinations could be engineered, for example at higher pressure, but currently would be limited by the capacity of the Hickam station (about 6,200 psig for this kind of high-volume filling).

The trailer itself will be filled at the Hickam station using the existing commercial 350 bar dispenser, using a manual fill process attended by an experienced, trained technician. The trailer's storage tubes would need to be US DOT certified (possibly via special permit) and the trailer inspected and licensed in Hawaii. It would be towed over public roads between Hickam and Young Brothers by an appropriately-certified driver.

5 Technical Assessment of the Deployment

This chapter describes the deployment of the generator at Young Brothers and presents the technical results and analysis of the generator's performance. It includes a description of the problems experienced with the generator and the impact of those and site operations on its operation, and makes recommendations for improvements in both areas. The chapter concludes with an assessment of the impact of the marine environment on the generator's physical condition.

5.1 Summary of Operations

The ultimate goal of the deployment was to have the generator power reefers on-board the barge that runs between Honolulu (Oahu) and Kahului (Maui). This was to be done in a staged approach, where each stage of operation would build familiarity and confidence before being deployed on the barge. The planned Stages were:

1. Have the generator run one shift with 6-8 empty reefers without incident at Icehouse for 1 full week
2. Power real product in a real rotation at the Icehouse for 2 weeks
3. Power 6-8 product reefers at the Maui barge dock for 2 weeks
4. Power empty reefers on the barge trip to Maui (2 trips, one way) for at least 16 hours each time
5. Power product reefers one-way to Maui
6. (Optional) Power product reefers round-trip to/from Maui (may be reduced load to allow hydrogen to last for the round trip).

The generator was commissioned in the Icehouse, the storage warehouse inside Young Brother's facility where products and goods are stored and organized before and after shipment. In October, 2015 it got to Stage 3 but suffered a technical issue with the inverter and was not able to run at that location. It was moved back to the Icehouse and remained there for the duration of the deployment due to continued technical problems (described fully in Section 5.3). Figure 34 shows an overhead view of the generator in the icehouse area, surrounded by white reefers.

Figure 34: The generator (blue) in the Icehouse area powering reefers (white).

5.1.1 Summary of Operating Days

During the 11-months deployment period, the fuel cell generator operated for 59 runs on 52 different days. Table 7 summarizes the operating days, time, hydrogen consumption, and output for the 59 runs. All runs occurred at the Icehouse.

Table 7: Summary of operation data during deployment

Date (MM/DD/YY)	Duration (HH:MM:SS)	H_2 Consumed (kg)	Average Power (kW)	Energy Produced (kWh)
8/4/2015	2:02:33	1.4	6.6	13.4
8/4/2015	6:49:57	16.4	26.9	183.5
8/6/2015	7:06:19	8.5	28.1	199.4
8/7/2015	10:01:18	8.4	23.0	230.8
8/8/2015	3:58:35	8	40.3	160.1
8/10/2015	4:00:22	17.2	65.5	262.4
8/11/2015	1:50:26	1.6	12.4	22.7
8/11/2015	1:29:28	4.6	48.6	72.4
8/11/2015	2:16:50	6	44.9	102.3
8/12/2015	4:06:49	6.3	41.3	169.9
8/13/2015	8:11:56	11.8	30.5	249.7
8/19/2015	4:42:05	0.2	8.4	39.4
8/20/2015	5:27:09	6.3	19.7	107.2
8/20/2015	2:04:26	1.5	14.9	31.0
8/21/2015	7:12:32	2.4	7.8	56.3
8/25/2015	2:41:40	2.4	15.8	42.6
8/25/2015	1:01:50	0.5	15.7	16.2
8/26/2015	1:14:44	1.7	17.1	21.3
8/27/2015	8:00:29	2.1	21.6	173.2
8/28/2015	2:25:38	3.2	24.0	58.3
8/28/2015	0:34:26	0.6	18.9	10.9
9/14/2015	7:02:20	15.9	39.5	278.0
9/15/2015	7:30:09	7.8	20.1	150.7
9/16/2015	6:16:21	7	21.0	131.7
9/22/2015	8:06:03	20.3	38.8	314.1
9/23/2015	8:29:54	19.9	39.4	334.7
9/24/2015	6:25:40	14.8	42.3	271.7
10/5/2015	0:09:45	0	0.2	0.03
10/7/2015	0:10:56	0.1	1.6	0.30
10/9/2015	0:07:30	0.1	0.5	0.1
11/13/2015	5:30:44	8.5	26.1	144.0
1/7/2016	8:13:07	18.1	38.1	312.8
1/11/2016	9:12:32	12.1	23.7	218.3
2/10/2016	7:02:44	9.4	20.4	143.8
2/12/2016	5:01:28	9.1	28.3	142.1
2/13/2016	11:21:02	12.1	27.0	306.8
2/16/2016	1:14:21	2.4	32.7	40.5
2/22/2016	0:30:33	0.1	1.5	0.8
2/23/2016	4:57:26	0.7	0.4	1.8

Date (MM/DD/YY)	Duration (HH:MM:SS)	H_2 Consumed (kg)	Average Power (kW)	Energy Produced (kWh)
2/25/2016	0:14:04	0.1	3.4	0.8
3/4/2016	4:16:26	5.3	47.6	203.3
3/7/2016	0:36:28	0	3.0	1.8
3/9/2016	6:14:14	12.7	36.2	225.5
3/11/2016	4:59:38	8.7	33.6	168.0
3/18/2016	2:28:02	0.7	0.0	0.0
3/18/2016	0:09:34	0	6.6	1.1
3/29/2016	5:53:27	5.2	15.7	92.7
3/30/2016	11:21:11	15.6	20.6	234.3
3/31/2016	7:54:06	14.1	29.2	230.9
4/1/2016	7:47:51	15.4	33.9	264.1
4/4/2016	9:08:02	2.1	19.1	174.0
4/8/2016	0:10:44	0.1	2.2	0.4
4/22/2016	1:06:57	0.5	7.0	7.8
4/23/2016	0:27:46	0.6	5.7	2.6
4/27/2016	8:35:00	13.9	26.6	228.7
4/28/2016	7:32:56	10.6	22.5	169.6
4/29/2016	8:38:11	12	23.1	199.8
6/7/2016	0:16:36	0.1	3.67	1.0
6/8/2016	3:58:01	2.9	15.5	61.3

5.1.2 Summary of Fueling Days

The fuel cell generator was refueled 8 times during the deployment period. Table 8 summarizes the refueling days and conditions. The total amount of hydrogen refueled during deployment was approximately 428 kg. Figure 35 shows a typical profile of the temperatures and pressure behavior during a refueling process. Refueling details including explanation of the temperature and pressure

Table 8: Summary of refueling days

Fill #	Date	Start Time [hh:mm:ss]	End Time [hh:mm:ss]	Fill Time [min]	Fill Seconds [sec]	Initial Mass [kg]	Final Mass [kg]	H_2 Filled [kg]
1	8/3/15	21:05:22	22:00:49	0:55:27	3327	0.3	63.2	62.9
2	8/8/15	12:40:58	12:59:14	0:18:16	1096	19.9	61.1	41.2
3	8/17/15	8:02:01	8:23:53	0:21:52	1312	13.9	61.6	47.7
4	9/21/15	13:07:21	13:38:31	0:31:10	1870	4	64.5	60.5
5	9/29/15	7:59:08	8:31:32	0:32:24	1944	7.9	50.4	42.5
6	2/9/16	8:39:27	9:07:25	0:27:58	1678	9.7	66.4	56.7
7	3/17/16	8:36:21	9:08:11	0:31:50	1910	5.7	67.3	61.6
8	4/11/16	8:25:02	8:54:18	0:29:16	1756	12	66.6	54.6

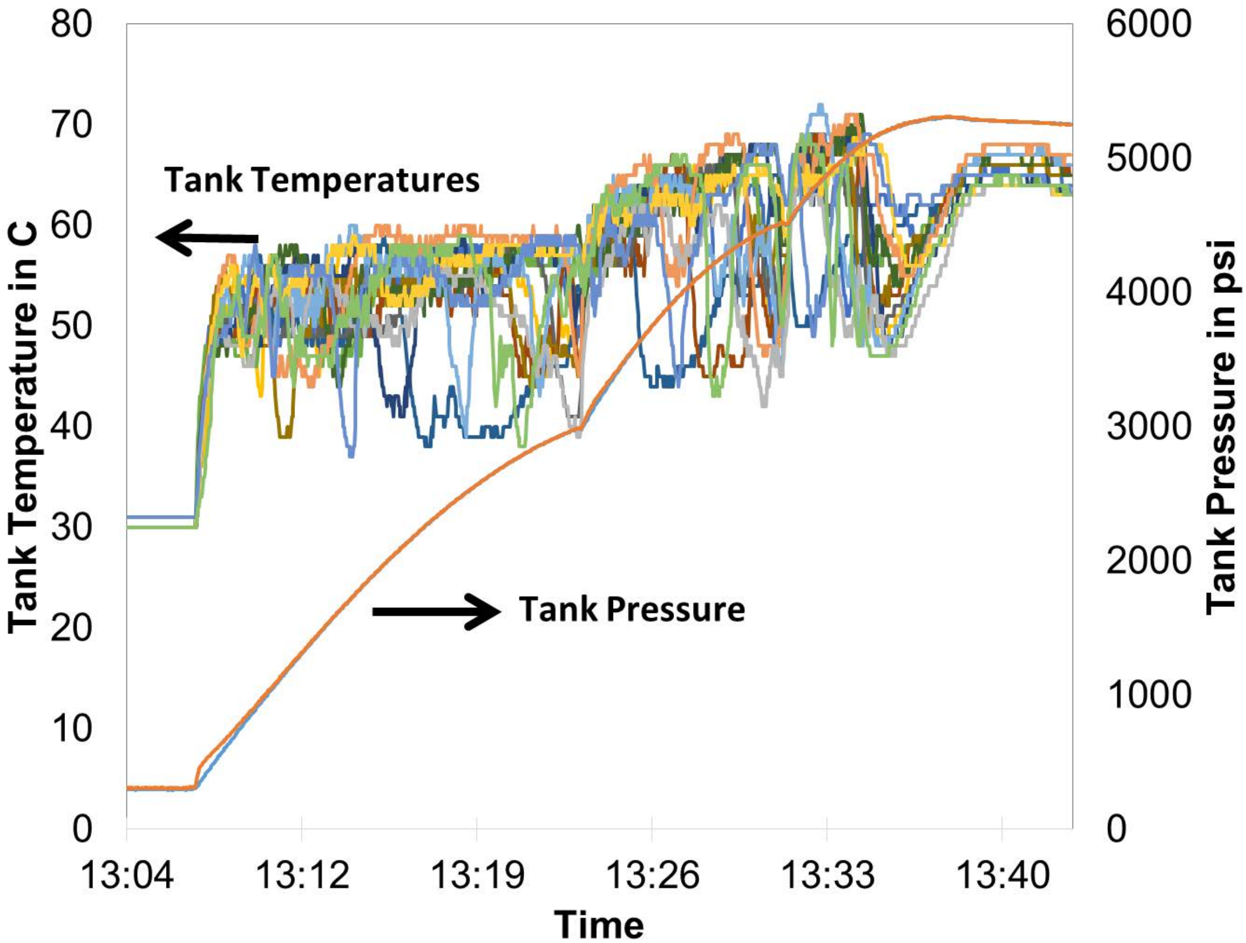

Figure 35: Fill data example (September 21, 2015)

change behavior is described in more detail in Section 5.2.5.

5.1.3 Deployment Weather

Weather and climate conditions for operation days were taken from online database from Weather Underground[9]. While temperature data were available for various locations in Honolulu, data were taken from temperature recordings at the Honolulu International Airport, which was the closest location to the fuel cell generator. The typical features of Honolulu's climate include fairly mild temperatures throughout the year, high humidity and frequent trade winds from the Northeast.

A tabulation of weather for the days the fuel cell generator was in operation is given in Appendix J. Temperatures for most operating days were fairly warm with moderate humidity as summarized in Figure 36 and Figure 37. No correlation was found between daily weather and generator efficiency for the data available. This is likely due to the relatively constant weather during the deployment.

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[9] Weather conditions taken from Underground Honolulu International Airport database, https://www.wunderground.com/history/airport/PHNL/2016/3/11/DailyHistory.html?req_city=Honolulu&req_state=HI&req_statename=&reqdb.zip=96801&reqdb.magic=1&reqdb.wmo=99999

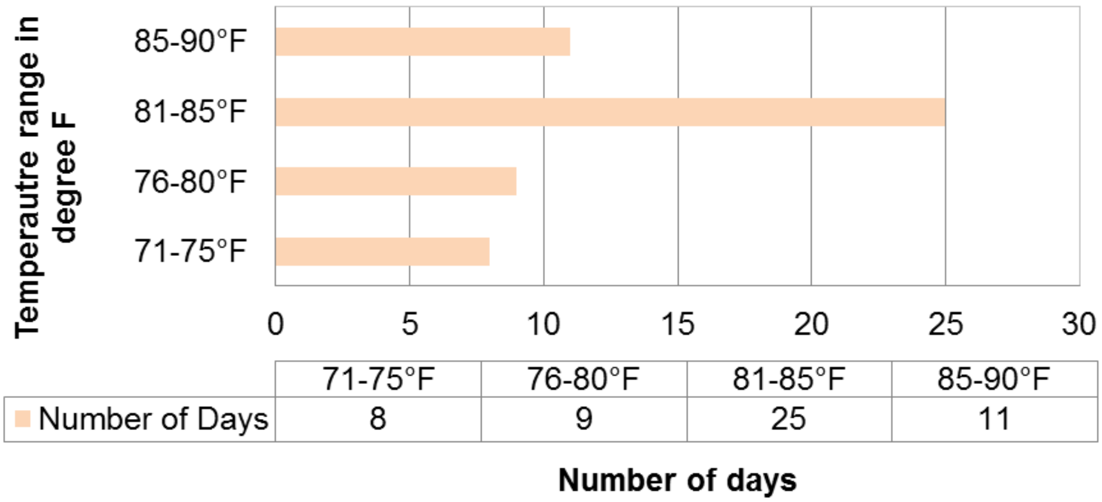

Figure 36: Temperature distribution for operating days

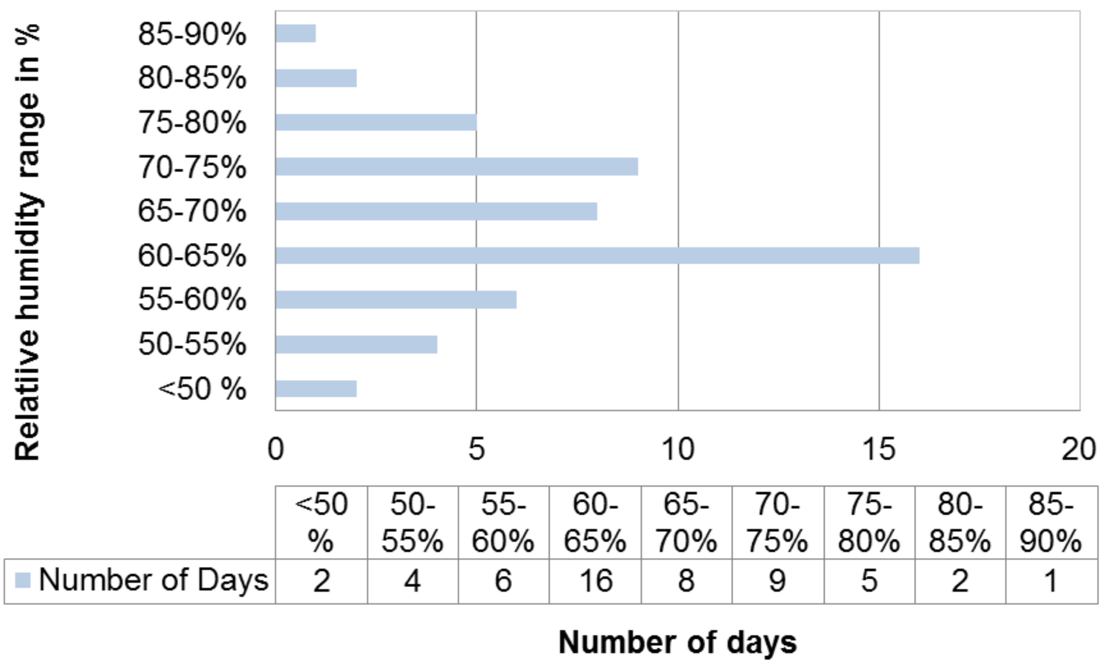

Figure 37: Relative humidity distribution for operating days

5.2 Performance Characterization

5.2.1 Reefer Power Demand

The reefer power demand varies during its operation. Part of this is due to various motors starting and stopping in a refrigeration system designed to maintain optimum balance between cooling and efficiency. These motor starts and stops cause short duration spikes in power demand, which were described in Section 3.1.2. In addition, longer term power demand transients are observed as the reefer cools down from a warm state to a steady-state cold setpoint. This type of cooldown can be observed when warm, un-used reefers are cooled down prior to loading them with goods. It can also be observed on a shorter time scale when doors are opened to add or remove goods. Finally, the refrigeration systems on the reefers have built-in diagnostic and maintenance routines that periodically run in order to keep the system operating correctly. An example of such a routine is heating the internal heat exchange coils to remove ice formed on their surfaces.

The combination of these routines can make it difficult to predict the power demand of a single reefer at a given point in time. When multiple reefers are connected at the same time, the effects become confounded with each other making it impossible to determine from power data alone what is being consumed by any individual reefer. For this reason, usage logs were also kept manually (Appendix F). The usage indicated on the usage logs can be overlaid on top of power monitoring data. An example of this is shown in Figure 38.

Figure 38 shows the power output from the generator from the time it was started with six reefers, and throughout the run as reefers were unplugged. In this run, all six reefers started warm, causing a peak power of 84 kW (average of 14 kW per reefer) upon startup. As the reefers cooled down over a period of about two hours, the power output stabilized around 42 kW (7 kW per reefer). Short term fluctuations of +/- 5 kW are visible during most of the run illustrating the high frequency of motor stops/starts. As reefers are disconnected, the total power declines. When only two reefers remain and

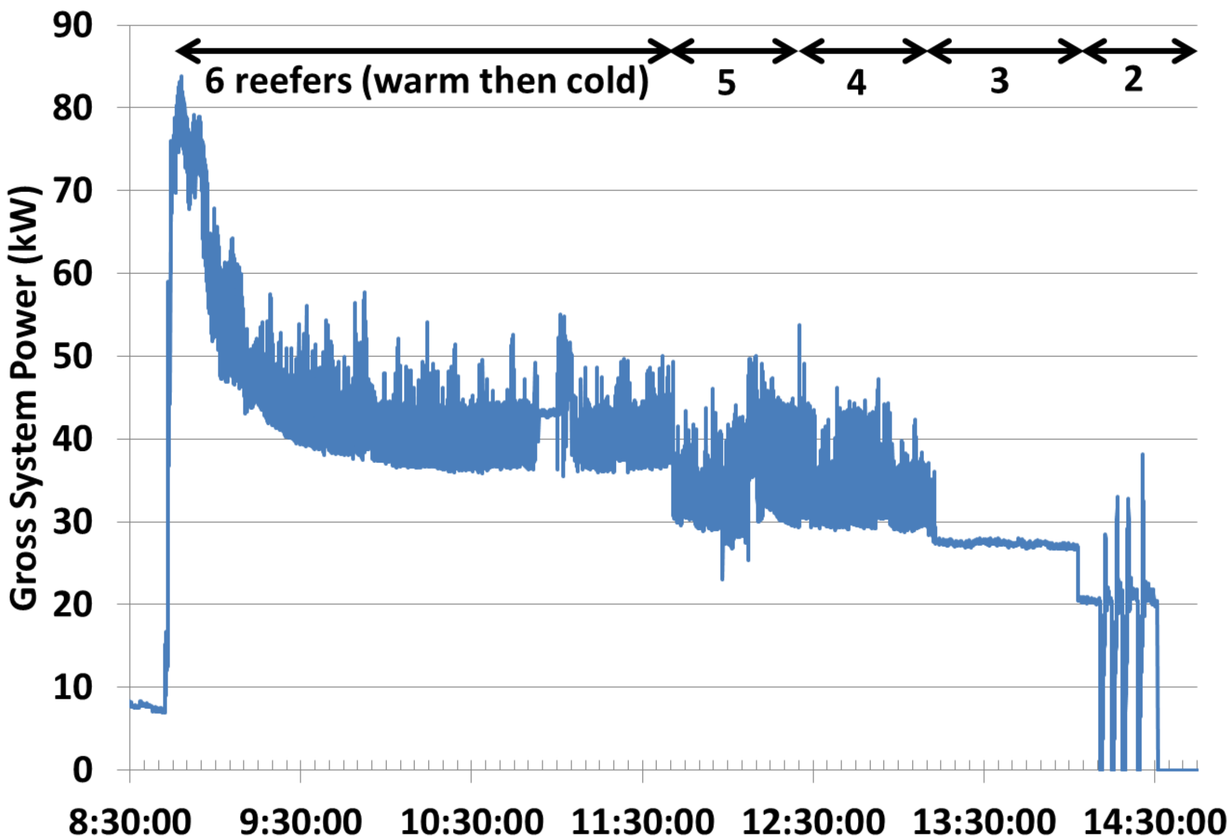

Figure 38: August 13, 2016 run showing typical variation of reefer load demand with time and number of reefers.

both are at steady-state, there are periods where neither reefer is drawing any power and the generator goes into standby with no power output.

The complicated behavior of the reefers ultimately had little if any effect on the performance of the generator and its ability to meet the load demands, with one exception. The generator was rated for a net apparent power output of 100 kVA. With a perfect power factor, this would match the real power in kW. However, monitoring of the reefer power consumption showed a low power factor, lower than 0.5 in some cases [15], and data from the deployment showed power factors ranging from 0.6 and 0.95, but usually in the range of 0.80-0.85. This means that while the generator may be supplying, for example, 80 kW of real power to the reefers, when the power factor is 0.8 it will actually be operating near its limit of 100 kVA.

The result of these two effects (a) warm reefers consuming 2-times more power than cold reefers (~14 kW each versus ~7 kW each) and (b) the low power factor, means that the generator is not able to meet the load demand of more than 6-8 warm reefers simultaneously. Because of this, operators were instructed to cool down reefers in stages, limiting the number of warm reefers to six, a mix of warm and cold to eight, and able to reach 10 reefers when at least eight are cooled down. For Young Brothers this was a manageable solution, because the only place where reefers were not already chilled was at the icehouse, where it was already common to stage initial cooldown of multiple reefers, and there are also grid power outlets available if needed. Although never able to be verified, when the generator was to be used in the staging area of the pier close to the barge or on the barge itself, the reefers were already chilled to their setpoints and it was not anticipated to be a problem in those situations either.

5.2.2 Generator Power Output

Generator run time, power, and energy production is summarized in Table 9 for the deployment period.

Table 9: Summary of generator performance during the deployment period

Total run time	278	hours
Maximum continuous run time	11:21:11	hh:mm:ss
Average gross power	29.4	kW
Maximum gross power[1]	91.3	kW
Total kWh generated	7,285	kWh
Total hydrogen consumption[2]	390	kg
Total hydrogen consumption	12,987	kWh

[1]For at least 5 continuous minutes

[2]Total hydrogen consumption is lower than total hydrogen filled as shown in Table 8 because of hydrogen left in the tanks at the end of the deployment as well as small differences in hydrogen consumption and fill calculations. See Section 5.2.6 for more information.

Figure 39 depicts the cumulative total hours of the fuel cell generator during the deployment period. The cumulative run time of the fuel cell generator was 248 hours. On average, the generator was producing 21.6 kW on days it ran. The total energy generated was 7,285 kWh, shown in Figure 40. The maximum reefer powered at a time by the generator was 10 and the minimum was 2. The maximum continuous run took place on March 30, 2016 with a runtime of 11 hours, 21 minutes, and 11 seconds, at an average of 20.6 kW output.

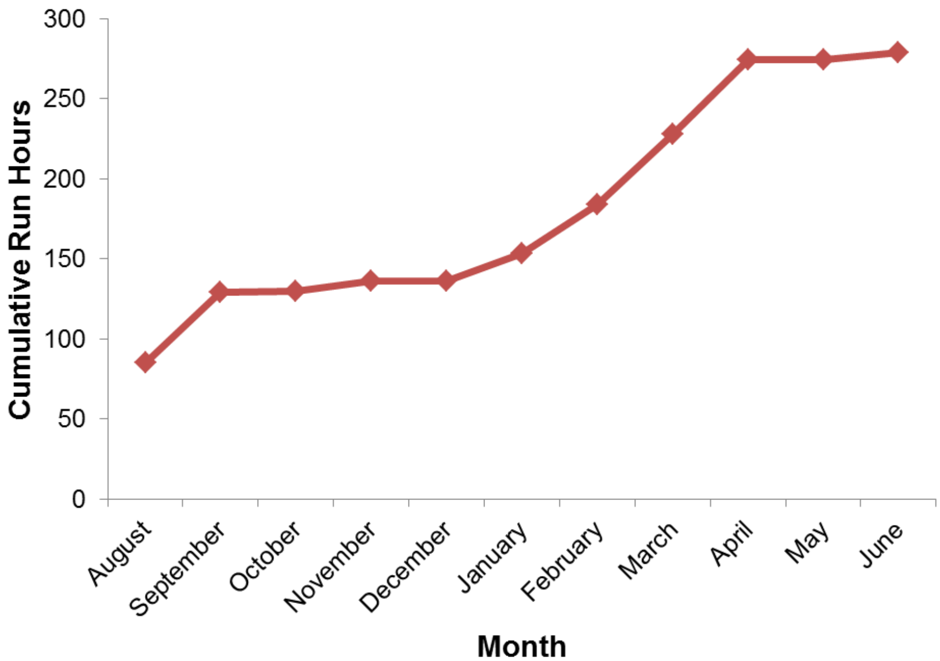

Figure 39: Cumulative run hours of fuel cell generator during deployment

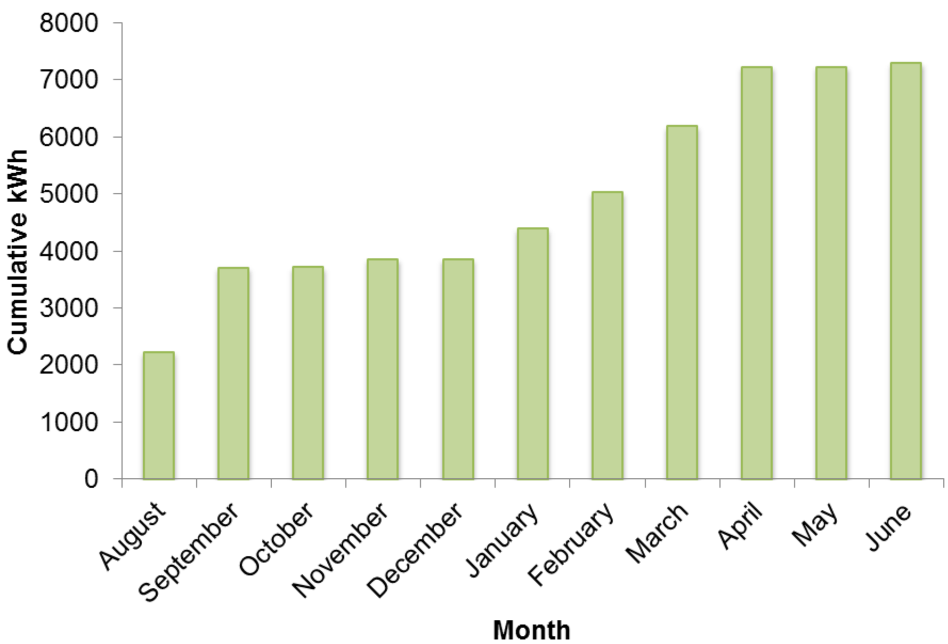

Figure 40: Total cumulative energy produced by fuel cell generator over the deployment period.

5.2.3 Generator Efficiency

Figure 41 and Figure 42 show the gross and net efficiency curve versus number of reefers and output power, respectively. The efficiency curve was constructed from taking different time periods in which reefers are plugged in and drawing steady power from the generator – that is, when the reefers were at their cold setpoint. Because of the transient nature of the power demand during cool-down, efficiency was not able to be obtained at other operating points because hydrogen consumption information is not available in the time resolution needed.

The gross and net powers were calculated for each time period and the efficiency was the computed using the fuel flow rate (calculated from the data of hydrogen in the storage tanks) and lower heating value of hydrogen. The net efficiency is computed by taking away the parasitic losses from the gross power output (described below). The gross efficiency ranged from 43% to 60% while the net efficiency ranged from 36% to 54%, with peak efficiency occurring near 30% load.

Gross power is the AC power out of the inverter. As can be seen from Figure 15 in Section 3.3, some of this AC power is used for internal systems (parasitic power). Net power is defined as power sent to reefers and is calculated by subtracting parasitic power from gross power.

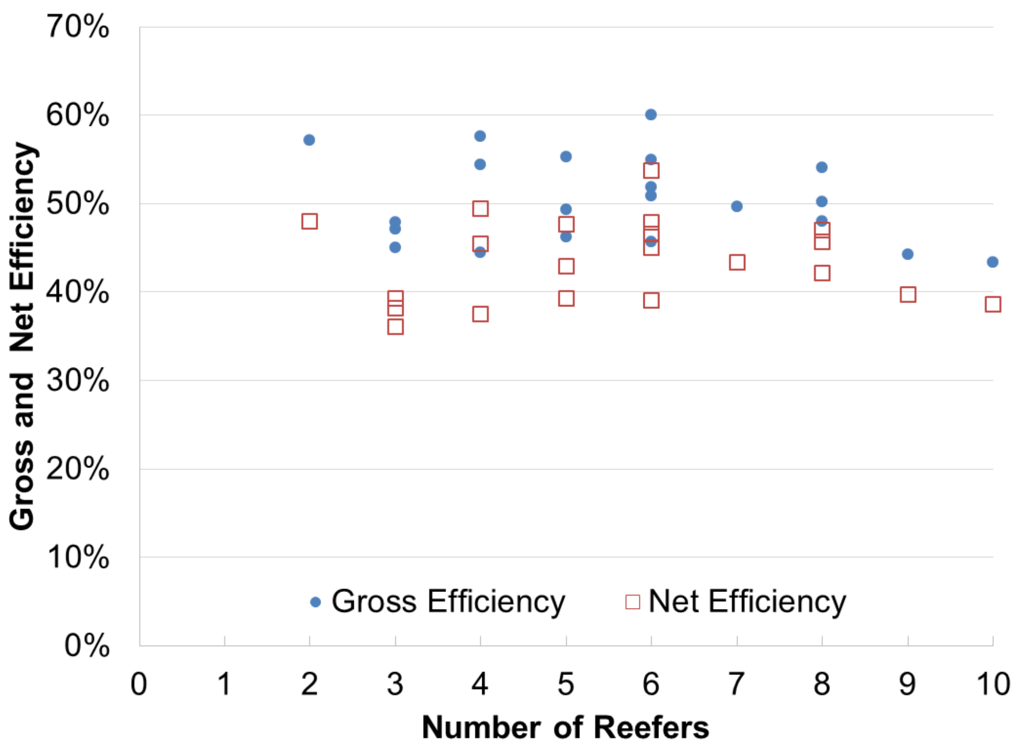

Figure 41: Gross efficiency (solid circles) and net efficiency (open squares) by number of reefers

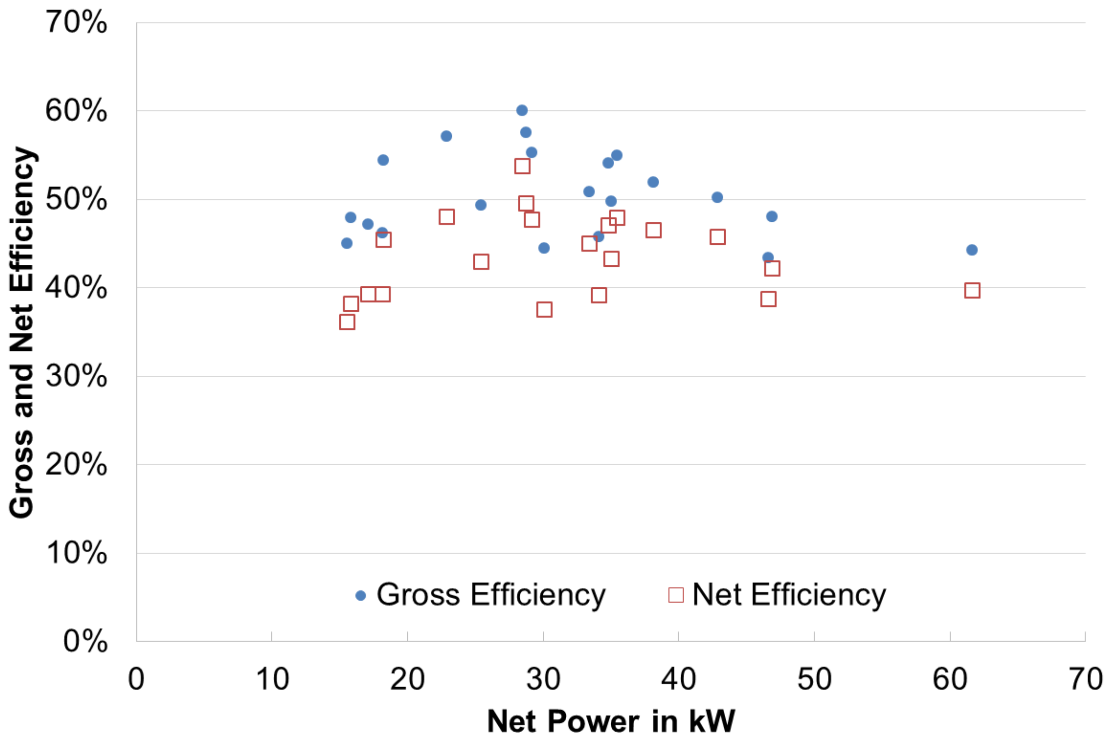

Figure 42: Gross efficiency (solid circles) and net efficiency (open squares) by net power

A list of parasitic losses for the system is shown in Table 10. There are four components that were assumed to have a fixed parasitic power output: internal ventilation fans (x2), fuel cell rack, systems controls, and the power supply. Their values were obtained from Hydrogenics and are based upon the rated power output of each component. The total fixed parasitic power for the four components is 722 Watts. Power consumption for the three other components varied over time and data were available to estimate these. The parasitic power for the 16 radiator fans and the exhaust fan was obtained by taking the average power consumption of each component over the evaluated time period. For the coolant pump, the average mass flow rate was computed to determine its parasitic power using the pump curve from the manufacturer. The coolant pump curve (Grundfos CRE20-2) can be found in Appendix K. Table 10 summarizes the source of parasitic power loses in the system.

Table 10: Summary of parasitic power losses in the generator.

Component	Parasitic Power	Reference
Internal HVAC fans x 2	186 W	Hydrogenics
Fuel cell rack	150 W	Hydrogenics
System controls	100 W	Hydrogenics
Power supply	100 W	Hydrogenics
Exhaust fan	varies slightly, typically ~50 W	Data
Radiator fans x16	varies widely, mostly as a function of power, 1 kW-6kW total	Data
Coolant pump	varies slightly, typically 1.5 kW	Data and Pump curve

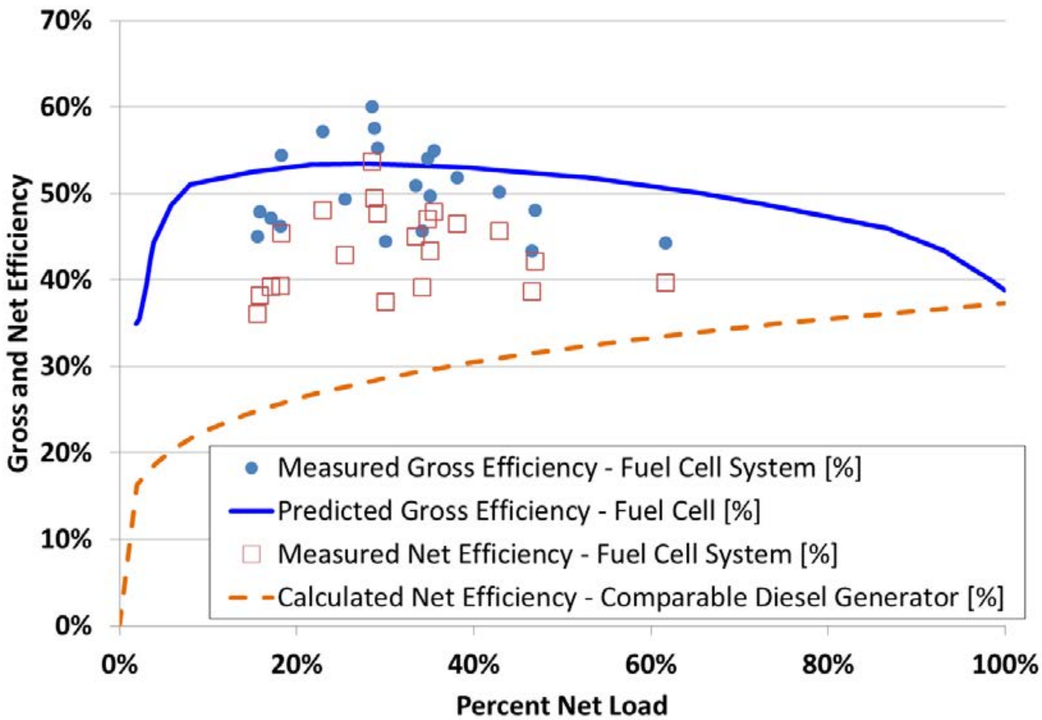

Figure 43: Comparison of measured fuel cell efficiencies with predicted fuel cell efficiency (solid blue line) and comparable diesel engine efficiency (dashed orange line). The measured gross efficiency compares well with the predicted fuel cell efficiency. The measured net efficiency of the fuel cell system shows a higher efficiency than the diesel generator at part load, and nearly 30 percentage points higher at the ~30% net load point.

It can be seen from Figure 42 that efficiency values vary widely near the same power level. This is true with both gross and net efficiency, which indicates that while fluctuations in parasitic power consumption may have some effect, they are not the primary cause. The likely explanation is the uncertainty in calculated hydrogen mass at the beginning and end of the run. Hydrogen consumption was estimated from the data, which calculates the mass of hydrogen in the tanks based on a bulk temperature measurement in the hydrogen room and pressure measured in the supply manifold. A 1 °C temperature change in the hydrogen room sensor can change calculated hydrogen mass by 0.1 kg or more. For a short-duration run where ~1 kg or so of hydrogen was used, this can have a large impact on estimated hydrogen consumption and as a consequence, the calculated efficiency.

Figure 43 combines the efficiency measurements from Figure 42 with the predicted efficiencies of the fuel cell modules and comparable diesel generator from Figure 2. Doing so illustrates how the measured gross fuel cell efficiency compares to that predicted by the manufacturer for the fuel cell modules (gross efficiency), and how net fuel cell generator efficiency compares to the net efficiency of a comparable diesel engine generator. The measured gross efficiency compares well to that predicted by the module performance. The measured net efficiency shows that the fuel cell system has a consistently higher efficiency over the diesel generator at part loads, with the efficiency benefit approaching 30 percentage points at the 30% load point.

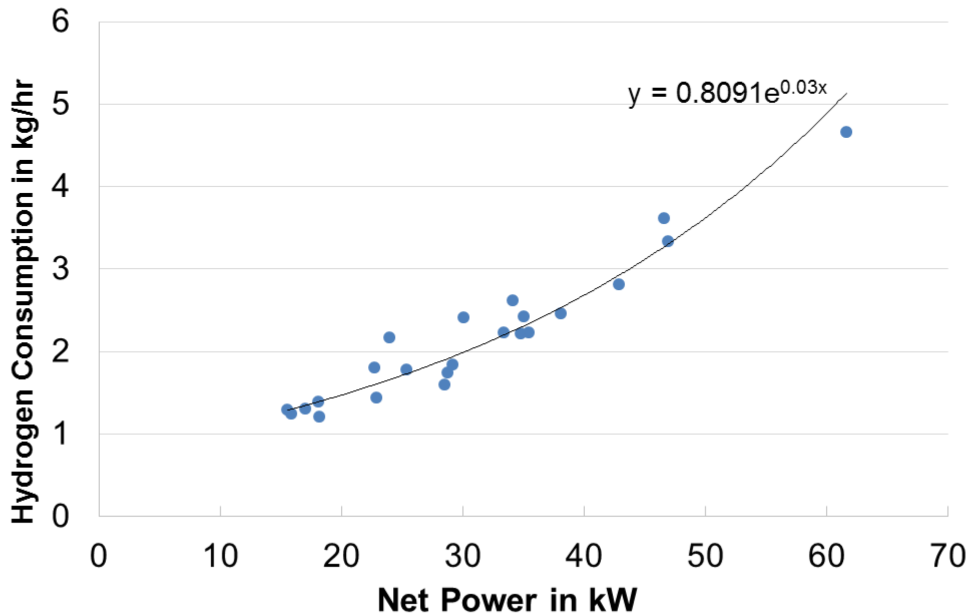

Figure 44. Fuel consumption curve versus net power

Figure 44 shows the estimated fuel consumption in kg/hour versus net power. Fuel consumption follows the expected trend for fuel cell systems. At very low power the parasitic losses are a larger fraction of the total power generated, leading to a flatter slope of hydrogen consumption at lower power levels because of lower system (net) efficiency. As power increases efficiency peaks near 30% load (30 kW in this case) and the slope begins to increase at a faster rate as output power continues to climb and fuel cell (gross) efficiency decreases.

5.2.4 Avoided Emissions

This section quantifies the exhaust emissions displaced by using a fuel cell generator instead of a diesel generator at Young Brothers for the deployment. A Caterpillar C15 350kW Tier 3 Diesel Generator was determined to be comparable to existing diesel generator sets at YB. Diesel generator emissions data for NOx, CO, HC, PM was obtained for this generator and varies over the load range as shown in Figure 45. Since the fuel cell generator uses pure hydrogen, there are no greenhouse gases or pollutant emissions produced at the point of use. The emission displaced by using a fuel cell generator is therefore exactly equal to the emissions produced from the diesel generator operating at the same power and producing the same energy. SOx emission data was calculated assuming all sulfur contained the Ultra-low-sulfur diesel (ULSD) fuel is converted to SOx. Table 11 shows the total displaced emissions for the deployment using the fuel cell generator's power and energy production as shown in Table 7 assuming that the fuel cell generator is displacing the use of a 350 kW diesel generator as typically used by Young Brothers. Use of the generator also displaced 865 gallons of diesel fuel.

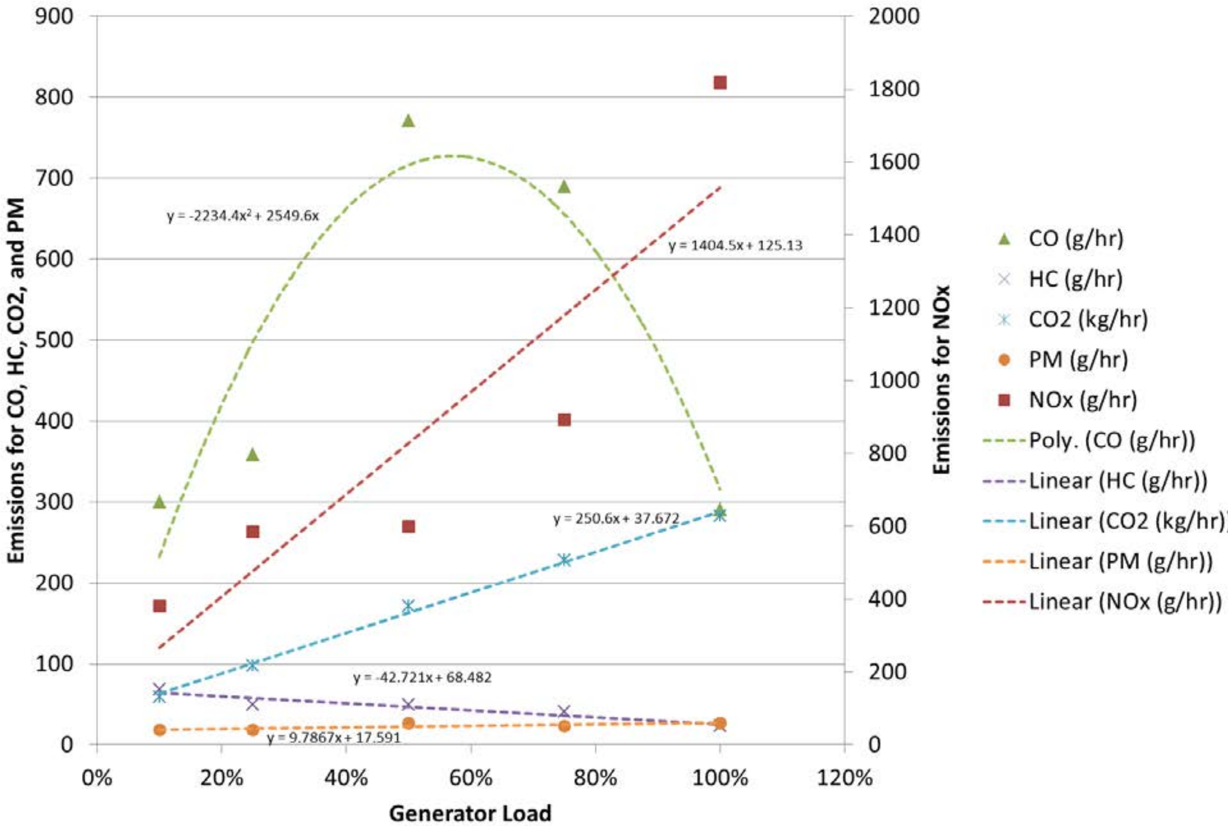

Figure 45: Variation of pollutant emissions as a function of load for a Caterpillar 350 kW C15 diesel genset.

Table 11. Total displaced emissions of fuel cell generator versus diesel engine during the deployment

	NO_x	CO	HC	PM	SO_x	CO_2
Displaced Emissions	68.5 kg	56.3 kg	17.8 kg	5.1 kg	2.3 g	16,400 kg

In practice, reefers at the Icehouse are normally plugged into the electric grid and not into diesel generators. Since the fuel cell generator operated exclusively at the Icehouse for the entire deployment, an argument could be made to consider the electric grid emissions rather than assuming power provided by a diesel generator. However, it should be noted that the Hawaiian electrical grid sources its power primarily from oil (71%) and coal (15%).[16] Therefore not only does estimating the avoided emissions assuming diesel generator illustrate the potential for fuel cell emissions avoidance if it were to directly displace a diesel generator, in actuality the emissions avoided from diesel generation may not be very different than that avoided from the grid.

5.2.5 Generator Refueling

The fuel cell generator was powered by hydrogen supplied from the Hawaii Center for Advanced Transportation Technologies. The hydrogen is in-part produced by electrolysis using electricity supplied from Hickam's solar-powered electric grid. The hydrogen refueling station is located at the Hickam Air

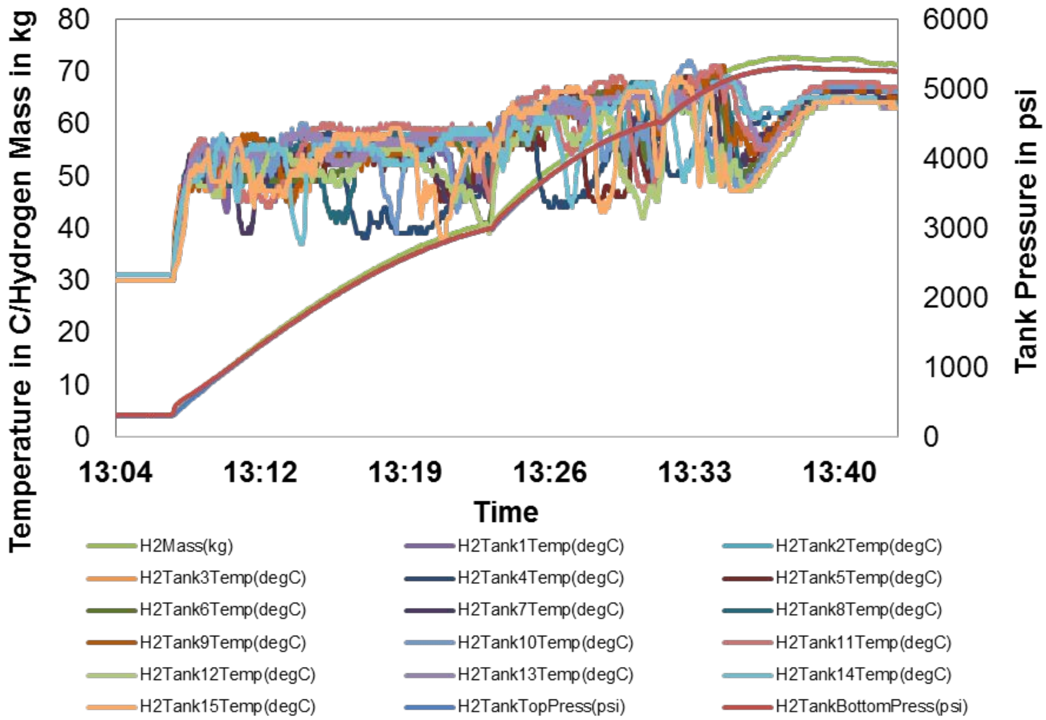

Figure 46. Fueling data from September 21 hydrogen refueling

Force Base located about 7 miles from the port. For each refueling, the generator is placed on a chassis (wheeled trailer frame) and trucked to the Hickam Air Force Base. Fueling takes place through an automotive-standard 350 bar dispensing nozzle and receptacle and hydrogen detection mode is enabled to monitor the tank temperatures and pressures.

Figure 46 shows the typical temperature and pressure variations during a fueling process. Switching the station's storage tanks during the refueling pauses the hydrogen flow into the tanks and can be seen as kinks on the mass and pressure curves (in this case at about 13:23 and 13:32). The temperature fluctuations are due to the opening and closing of the check valves on the tanks and are described more below in Section 5.2.6.4.

Table 12 summarizes the amount of hydrogen filled during deployment and the respective fueling rate. The fill rates ranged from 1.1 to 2.3 kg/min, with the average fill rate at 1.8 kg/min.

Table 12. Hydrogen fill rate summary

Total Hydrogen Filled	428	kg
Minimum Fill Rate	1.1	kg/min
Maximum Fill Rate	2.3	kg/min
Average Fill Rate	1.8	kg/min

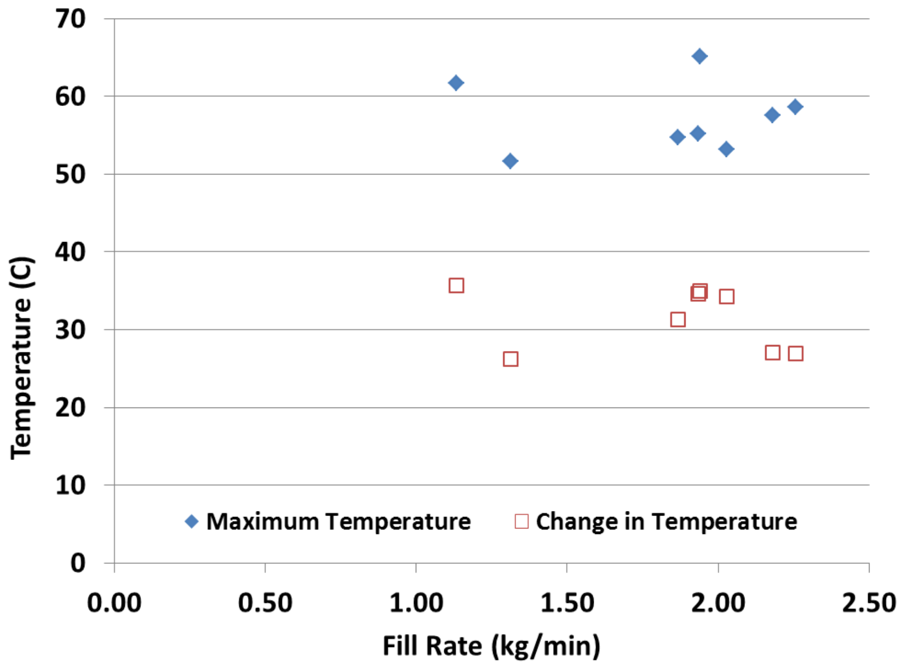

Figure 47: Effect of fill rate on maximum temperature and temperature rise of the hydrogen storage tanks.

The hydrogen storage tanks are Type III tanks, which are aluminum liners overwrapped with carbon fiber. This type of tank typically has better heat transfer characteristics than Type IV tanks (used on today's fuel cell electric vehicles), which have a polymer liner. The Type III tanks are heavier, but the heat transfer characteristics allow rapid filling without approaching the industry-standard 85 °C limit imposed on tanks today. Figure 47 illustrates the maximum temperature and rise in temperature experienced for all eight fills. No correlation between fill rate and maximum temperature or temperature rise can be observed in the range of values experienced. The data appear to indicate that the fill rate could be increased beyond the maximum to-date with little possibility of exceeding the 85 °C temperature limit.

5.2.6 Determining Amount of Hydrogen in the Tanks

Operators use the mass reported by the system controller to determine the amount of hydrogen in the tanks. It has been found that the reported mass can misrepresent actual hydrogen mass by about 5%, and more in certain conditions, due to differences in measured temperature and pressure versus actual temperature and pressure within the tanks, and because of a simplified mass calculation equation used by the controller. Considering the physical reasons for the differences in calculated and actual mass, it is recommended that the operator not rely on the system controller mass during the fueling process as it will over-predict the mass in the system. The operator should use the system controller mass at the first Leak Check following a fill to represent the mass at the end of the fill and/or the mass at the beginning of the next run. The manufacturer should change the equation used to calculate mass to a more accurate one, and if that is not possible, then a correction table should be given to the operator to make manual adjustments to the readings.

The remainder of this section describes the details of these findings.

5.2.6.1 *Hydrogen Mass Calculation Equation Error*

The hydrogen station does not measure dispensed mass, and the generator does not measure mass flow. Hydrogen mass in the tanks therefore must calculated using representative pressure and temperature measurements. The system controller uses the following simplified equation:

$$m = 603.015 * p * 0.00689512 / T$$

Equation 1: Hydrogen mass calculation used by the system controller.

where m is hydrogen mass (kg), p is measured pressure (MPa) and T is measured temperature (K).

Non-idealities of hydrogen at high pressures demand more complex equations to accurately calculate hydrogen mass. An accepted equation is the following from NIST [17]:

$$\Delta m = \frac{MV}{R}\left[\frac{p_{final}}{T_{final} z(p_{final}, T_{final})} - \frac{p_{initial}}{T_{initial} z(p_{initial}, T_{initial})}\right]$$

Equation 2: Hydrogen mass calculation formula as a function of T & P

where Δm is the change of the mass of hydrogen, *M* is the molar mass of hydrogen (g/mol), *V* is the water volume of the tank (L), *R* is the gas constant (J/mol-K), *P* is the pressure (MPa), *T* is the temperature (K), and *z* is the compressibility factor. The compressibility factor z is calculated from Equation 3 below [17], where the constants associated with the equation follow in Table 13.

$$z(p,T) = 1 + \sum_{i=2}^{6}\sum_{j=1}^{2} v_{ij}\left(\frac{p}{1MPa}\right)^{i-1}\left(\frac{T}{100K}\right)^{nij}$$

Equation 3: Density calculation formula as a function of T & P

For the tank volumes and typical pressures of hydrogen stored in the generator, the difference between the mass calculated by these two equations can be nearly 4 kg in certain conditions. Figure 48 graphically illustrates the total mass error given by the system controller equation for the range of conditions encountered with the generator. It can be seen that the simplified system controller

Table 13: Constants for use in the compressibility equation, Equation 3. From Ref. [17]

i	j	v_{ij}	n_{ij}
2	1	0.036719	−1.23
2	2	−0.039839	−2.22
3	1	−0.0014722	−2.68
3	2	0.002408	−3.1
4	1	0.65994×10^{-5}	−2.7
4	2	-0.15469×10^{-4}	−4.3
5	1	-0.13383×10^{-6}	−3.3
6	1	0.15608×10^{-8}	−4.1

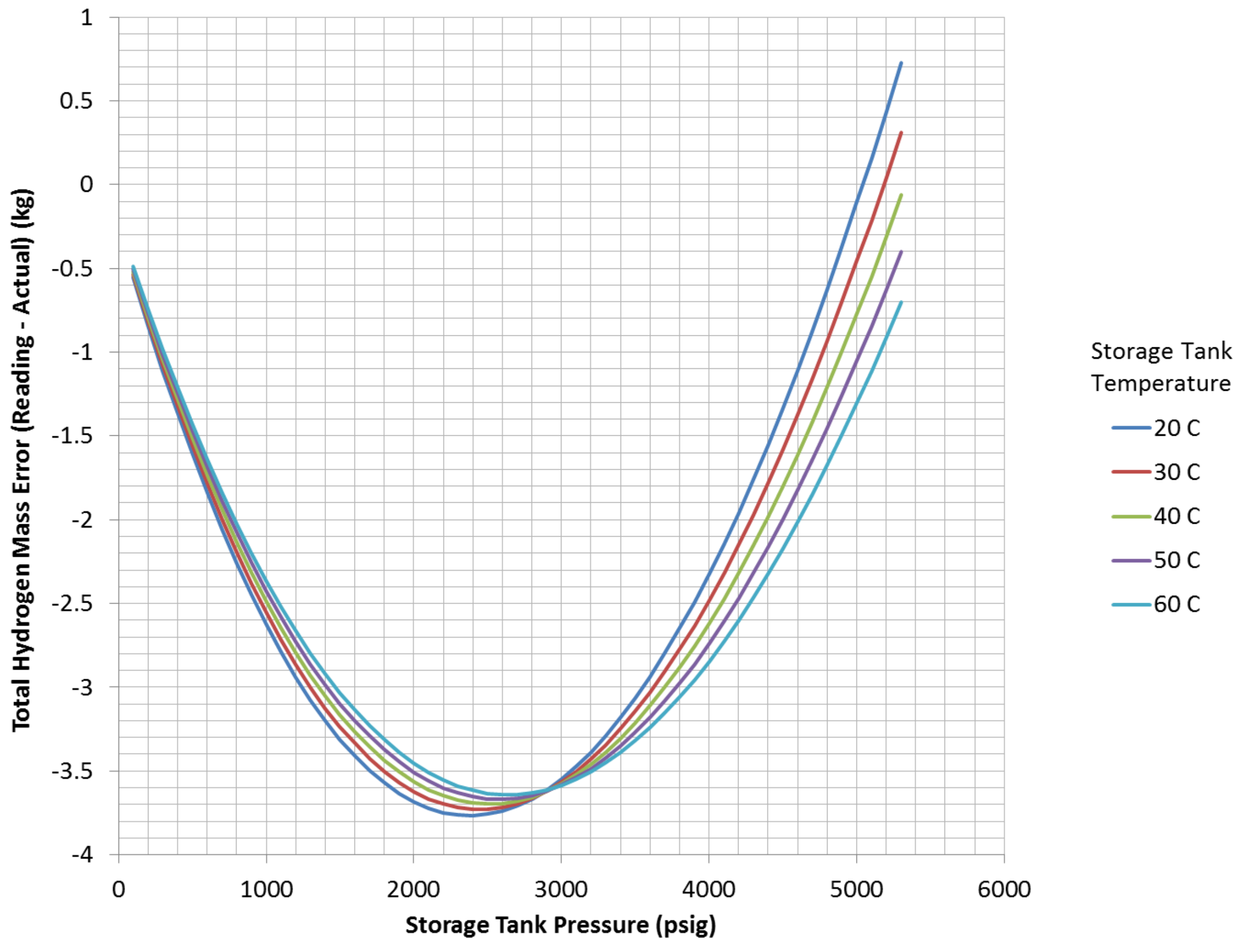

Figure 48: Total hydrogen mass error when using the value calculated by the generator's system controller as a function of storage tank pressure and temperature.

equation performs well at high and low pressures, but has substantial error (-10%) at medium (~2,500 psig) pressures.

5.2.6.2 Pressure and Temperature Measurements

Hydrogen pressure is measured at two points in the tank manifold. These points will represent actual pressure in the tanks only when the tank solenoid valves are opened, which only happens after the unit is started in power generation mode. During fill, the tank valves are closed and hydrogen enters the tanks from the manifold through integrated check valves on each tank. According to the tank valve assembly manufacturer, the tank check valves are supposed to open to allow flow into the tanks with a 30 psi differential ("opening pressure"). The actual opening pressure can be inferred from the data and has been estimated to be higher, sometimes reaching over 200 psi. This means that during and immediately after a fill, the pressure reading in the manifold is actually higher than that in the tanks and the calculated mass will differ from the actual tank mass.

In addition to the above effect, when the generator is unused small leaks in the manifold can significantly reduce the pressure in the manifold due to its small volume. This means that hydrogen mass calculations taken with pressure readings during this time will be artificially low.

The temperature also impacts the hydrogen mass calculation. There is a temperature transducer near the roof of the hydrogen storage room and this is used by the system to represent the temperature of the tanks. This is acceptable when the generator is in use and radiator-induced air flow through the hydrogen storage room helps to ensure constant temperature throughout the room and inside the tanks. However it will be in error when the generator has been sitting un-used and the temperature near the top of the room is higher than the tanks, and during fill when the temperature in the tanks is much higher than that in the room. In the latter case, using a lower-than-actual temperature will over-predict the hydrogen mass within the tanks. This error affects the hydrogen mass calculated by the control system. However, since there are also thermocouples within each tank, this can be corrected in post-processing of the data substituting the actual tank temperature instead of the storage room temperature.

A graphical description of the combination of these effects is shown in Figure 49. During each refueling, the system is switched on to "Hydrogen Detection" mode (Point 0). At this time the pressure in the manifold may be lower than the actual tank pressure due to small leaks in the manifold since its last use, giving an artificially-low mass reading at the pre-fill state. The fuel nozzle is plugged in and hydrogen begins to enter the storage tanks. During the fueling, hydrogen undergoes compression. Temperature and pressure in the tank increases as a result of the compression until the refueling stops (Point 1). During this time, the pressure in the manifold will be higher than the pressure in the tanks due to the check valve effect, giving an artificially-high mass reading. If room temperature is used to calculate mass during this time, it will indicate a lower temperature than what is actually in the tank and further increase the calculated mass. Once the fueling ends the tanks begin to cool down to ambient temperature (Point 2). The pressure in the manifold will likely be higher than what is in the tank, but may decrease over time due to leakage. Heat transfer takes place until the temperature of the tanks is

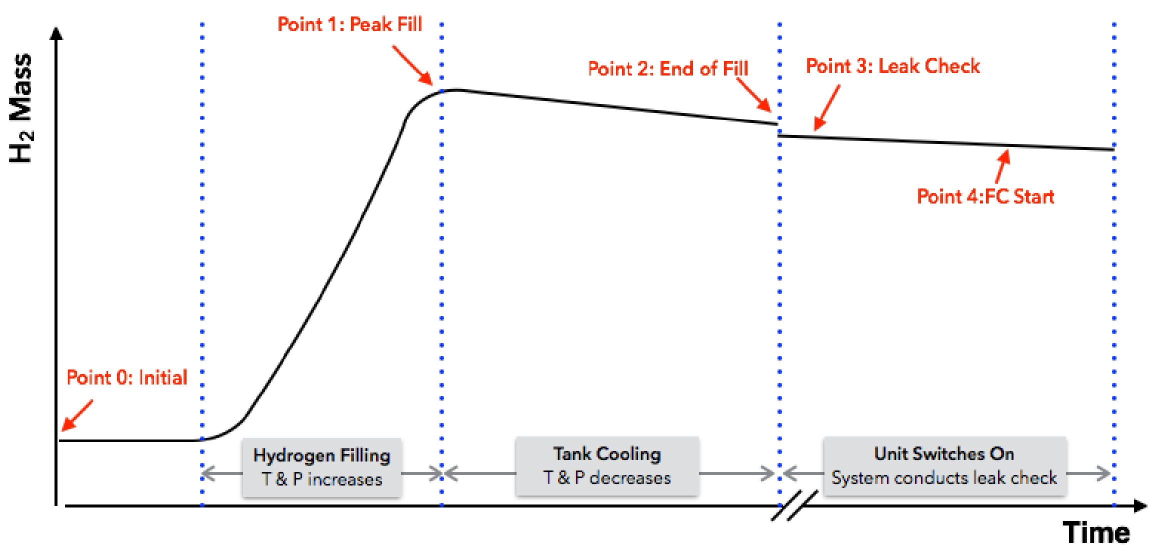

Figure 49. Temperature and pressure characteristics during hydrogen refueling

Table 14: Hydrogen mass in the generator's tanks as calculated by the system's controller, for different time points between which no mass has entered or left the tanks.

Fill Date	Point 1: Peak Fill	Point 2: End of Fill	Point 3: Leak Check
8/3/2015	66.4	63.1	63.2
8/8/2015	68.6	67.9	61.1
8/17/2015	68.0	63.8	61.6
9/21/2015	72.6	71.3	64.5
9/29/2015	55.1	52.0	50.4
2/9/2016	72.9	69.7	66.4
3/17/2016	75.6	62.8	67.3
4/11/2016	74.7	72.6	66.6

equal to the ambient temperature, so the temperature effect will go away over time. The next time the generator is turned on in power generation mode it undergoes a leak check test to ensure there is no hydrogen leak in the system (Point 3). During leak check one tank valve is briefly opened to charge the line with hydrogen at full tank pressure. At this point the hydrogen pressure in the manifold should be nearly representative of the steady-state pressure in the tanks, only differing due to tank-to-tank variations in pressure. The temperature in the room will be close to that of the tanks, so the mass calculated at the leak check point should give a good estimate of the actual hydrogen mass. Once the system passes the leak check (within a minute), all tank solenoid valves open (Point 4). At this point and during operation the pressure in the manifold is equal that in all the tanks. Unfortunately, because the system is running, it is also consuming hydrogen so while pressure readings can be used to accurately calculate the hydrogen mass at this and all times forward, it may under-predict the hydrogen in the tanks just before startup.

As described, each method of determining hydrogen mass has drawbacks that introduce uncertainty into the hydrogen mass determination. Table 14 shows the different hydrogen mass values given by the system controller for each fill at Peak, End, and Leak Check. From the figure it can be seen that the controller's own mass estimates vary by more than 10% depending on when the measurement is taken simply because the temperature and pressure measurements used in the calculation do not actually represent tank conditions for the reasons described above.

5.2.6.3 Cause and Effect of Temperature Discrepancies

To assess the temperature effect on these variations, each mass point was re-calculated using temperatures reported by each individual tank. Figure 50 shows the calculated mass of hydrogen at each fill point during the 9/29 fill, using the manifold pressure and individual tank temperatures and Equation 2 and Equation 3 rather than the system controller equation (Equation 1). For the sake of simplicity and space, only the 9/29 results will be highlighted here, since calculations for the other days yield very similar results. The general trend is that the calculated hydrogen mass is highest at the peak of fill (Point 1) since measurements exhibit the highest pressure and temperature at this point. However, the percent difference between each tank from peak of fill and end of fill is actually only about 2-3%.

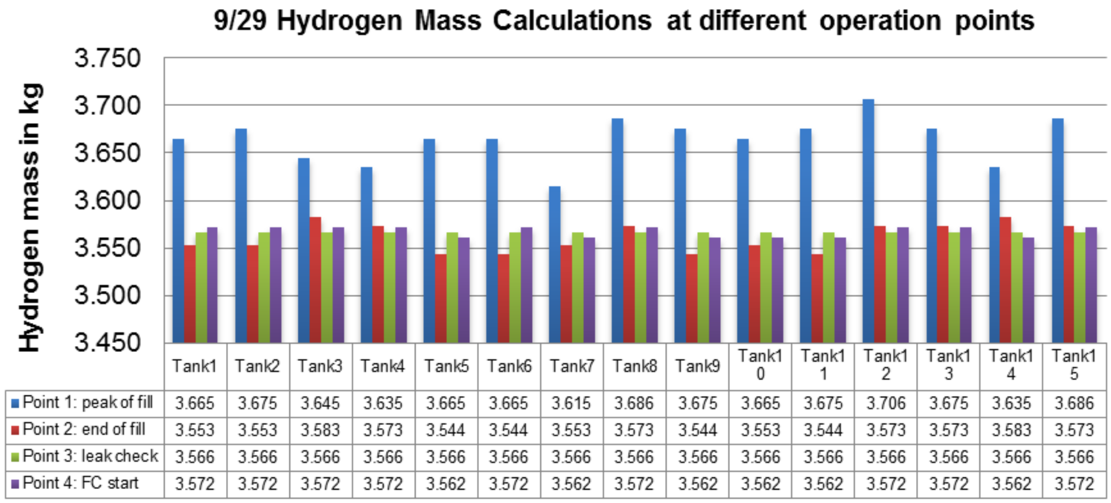

Figure 50. Hydrogen mass at different operation point for 9/29 fill. Note the Y-axis origin is not zero.

Table 15. Percent differences of calculated hydrogen mass for 9/29 fill.

Fueling process points	Tank														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$P_1 - P_2$	3.1%	3.3%	1.7%	1.7%	3.3%	3.3%	1.7%	3.1%	3.6%	3.1%	3.6%	3.6%	2.8%	1.4%	3.1%
$P_2 - P_3$	0.4%	0.4%	0.5%	0.2%	0.6%	0.6%	0.4%	0.2%	0.6%	0.4%	0.6%	0.2%	0.2%	0.5%	0.2%
$P_3 - P_4$	0.2%	0.2%	0.2%	0.2%	0.1%	0.2%	0.1%	0.2%	0.1%	0.1%	0.1%	0.2%	0.2%	0.1%	0.2%

Table 16. Comparison of calculated hydrogen mass to system controller for 9/29 fill

Operating Point	System Controller (room T, simplified equation)	Corrected System Controller (room T, correct equation)	Calculated (tank T, correct equation
Point 1: Peak Fill	55.5 kg	58.3 kg	55.0 kg
Point 2: End of Fill	52.0 kg	54.8 kg	53.3 kg
Point 3: Leak Check	50.4 kg	53.3 kg	53.4 kg
Point 4: FC Start	50.5 kg	53.4 kg	53.8 kg

Calculated hydrogen at the other points (end of fill, leak check, FC start) resulted in minor differences, about 0.1%-0.6%, as shown in Table 15.

Table 16 compares the calculated hydrogen mass using the system controller and room temperature ("System Controller"), correct equation and room temperature ("Corrected System Controller"), and correct equation and individual tank temperature ("Calculated"). The difference between the Corrected System Controller and Calculated values show the effect of using the room temperature rather than individual tank temperature. It can be seen that using room temperature over-predicts hydrogen mass during and just after fill, but that it well-represents actual mass when the unit is started sometime later and temperatures have had a chance to equilibrate. The Calculated values also show that, at Peak Fill, there is still an error resulting in over-predicted mass. This is explained in the next section.

5.2.6.4 Cause and Effect of Pressure Discrepancies

To understand why the hydrogen mass was calculated to be higher at Peak Fill, we analyzed the opening pressure of the check valves, which would cause a higher measured pressure (in the manifold) than what actually exists in the tanks. Figure 51 displays the temperature of the fifteen tanks during the entire fill. One important feature of the temperature data is the noticeable temperature fluctuations during the fill. This fluctuation is due to the opening and close of the check valves as a result of a hydrogen pressure gradient in the manifold. When the pressure in the manifold overcomes the opening pressure of the check valve, the valve opens and hydrogen flows into the tank, increasing its temperature. As tank pressure approaches manifold pressure, the check valve re-closes, hydrogen stops flowing, and temperature drops. The cycle repeats throughout the fill process.

According to the manufacturer, the check valve has an opening pressure of 30 psi, an indication that the measured hydrogen manifold pressure during fill used to calculate the hydrogen mass is at least 30 psi above the tank pressure. A number of tanks were examined for each of the fills to verify the actual opening pressure. Figure 52 and Figure 53 show an example of this analysis for Tank 2 and Tank 15 on 9/29. As seen from the two figures, the opening pressure varies significantly from tank to tank, and also from different points of the fill. This conclusion is consistent with the opening pressure analysis performed on the other fill days. The average opening pressure for the 7 tanks analyzed was

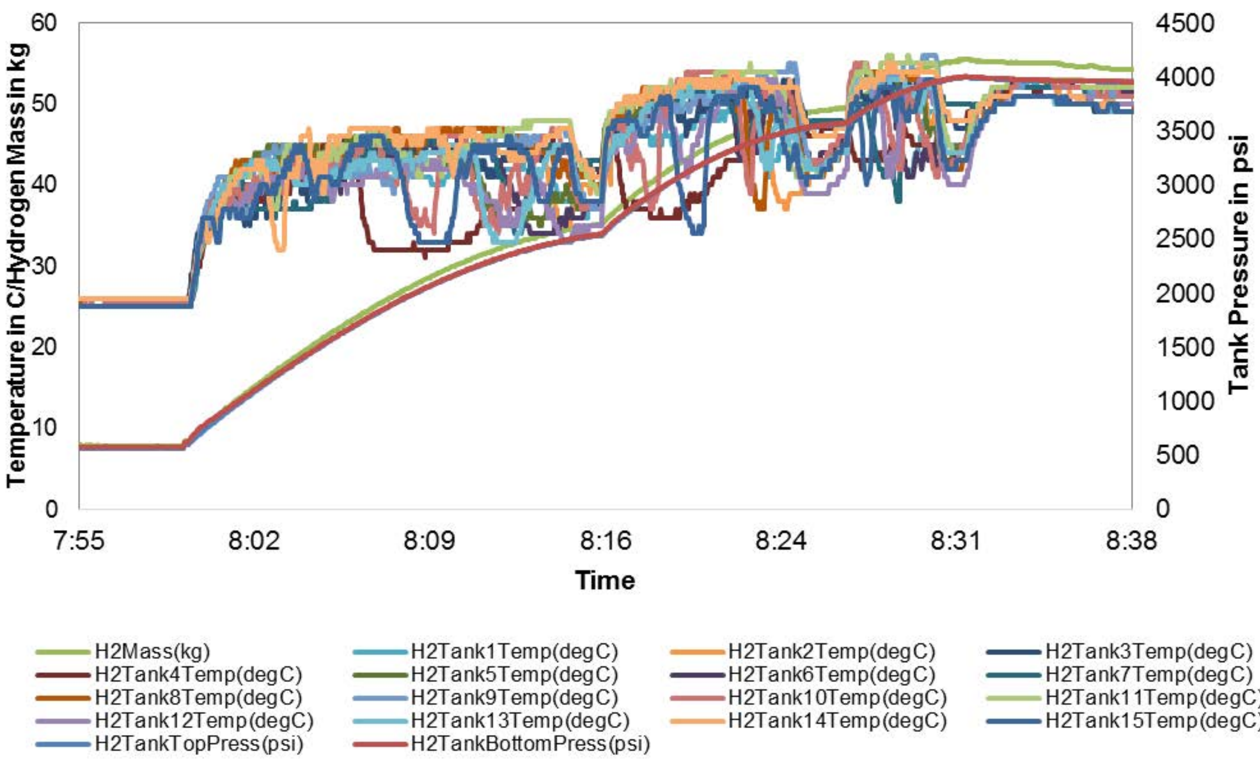

Figure 51. Temperature, mass, and pressure variation during 9/29 fill

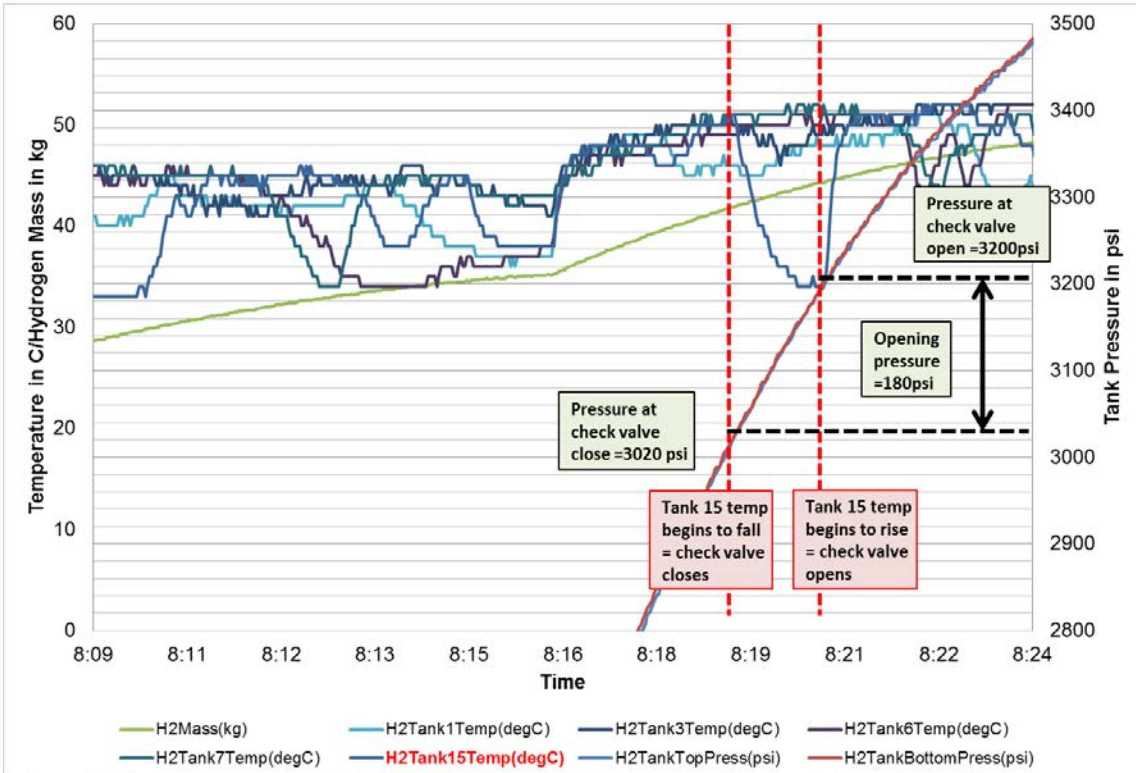

Figure 52. Opening pressure estimation for Tank 15 on 9/29 fill

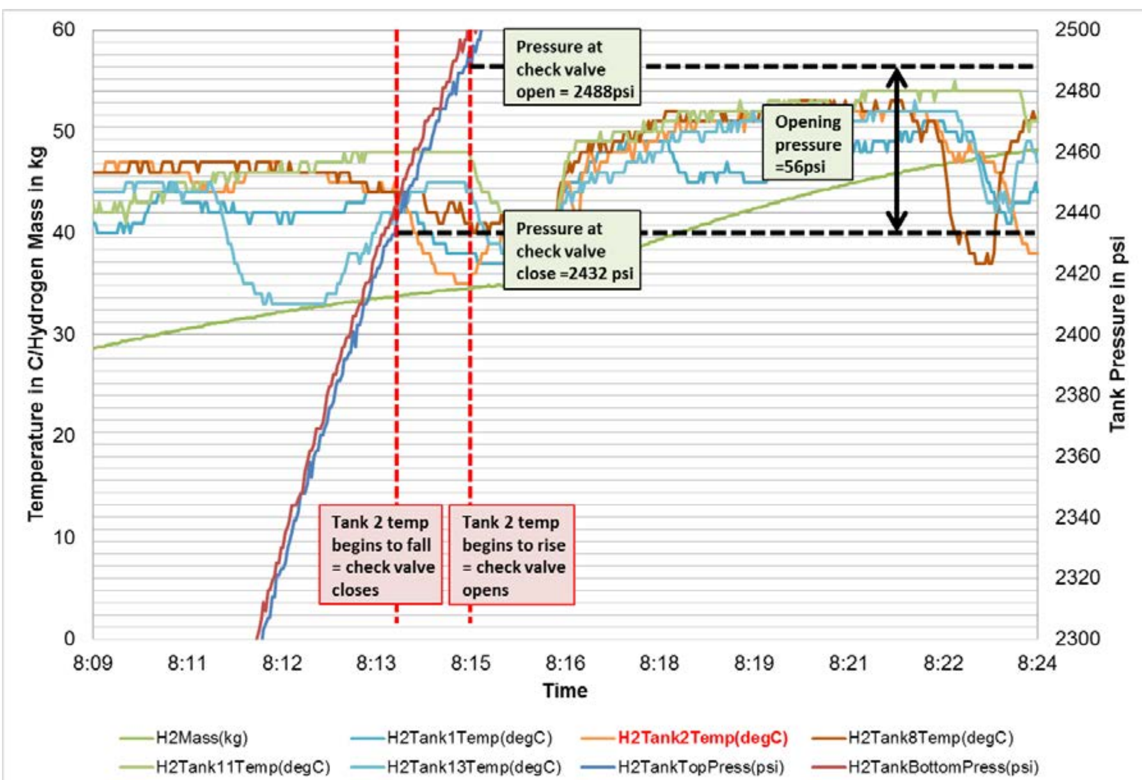

Figure 53. Opening pressure estimation for Tank 2 on 9/29 fill

approximately 148psi, meaning that, on average, the pressure in the manifold during and immediately following fill is 148 psi above actual tank pressure. Because the manifold pressure is used to calculate tank mass, it will over-predict the actual tank mass at these times. Reducing the measured pressure by 148 psi at Peak Fill results in a calculated hydrogen mass of 53.2 kg, consistent to the Calculated mass at Points 2-4 as shown in Table 16.

5.2.7 Operator Feedback

Based on qualitative feedback from Young Brothers personnel, it was agreed among the unit operators that the fuel cell generator works fairly well and generated positive responses from its usage at the port. The primary issue the operators experienced was troubles with startup, but once the unit is started, “it’s as good as a diesel gen”, according to feedback from one operator.

Another concern that operators voiced is the number of reefers that the fuel cell generator can power (6 to 10 reefers), while an existing diesel generator on site can power 25 reefers at once. With the fuel cell generator, the operators felt that a completely different skill set (e.g. mechanical, electrical, troubleshooting) and training was required for its operation and maintenance. Operators felt greater robustness were required for all of these areas, which would in turn improve the operation of the fuel cell generator at the port.

Another qualitative feedback concerns the loading and unloading of the truck for the hydrogen refueling. Some operators found the trucking process fairly inefficient, in comparison with the diesel generator refueling where the diesel trucks are readily available for refueling onsite.

The issue of hydrogen safety is often an area of concern in any type of fuel cell deployment. There was initially some general sense of skepticism of having hydrogen on site but operators felt that most people’s feedbacks were positive once they were better informed of the benefits of hydrogen compared to fossil fuels and learned that “hydrogen has been around for a while”.

5.3 Maintenance/Problems/Issues

As discussed in Section 5.2.2, the fuel cell generator produced 120+ hours of power during the first three months of deployment. Run time decreased in the months of November and December due to technical issues and insurance/liability agreement issues between Sandia and Young Brothers. The fuel cell generator experienced several start-up issues in January since the unit was not run for the previous two months, leading to low glycol coolant level and the fuel cell stack losing moisture through evaporation over time. In early March, the generator was moved back to the Ice House due to construction at the pier, causing space constraint and traffic issues. The unit finally returned back to normal operation in mid-March but start-up issues in the battery held back operation again in April. There was no run in May due to the battery troubleshooting. The unit began normal operation again in June.

This section explores the issues experienced during the deployment and ends with recommended actions for improved subsequent performance. (Issues experienced during commissioning are described in Section 3.5).

5.3.1 Issues with Fuel Cell Generator

A list of problems/issues related to the fuel cell generator during the deployment is summarized in Table 17. Figure 54 shows the downtime of generator-related components in approximate days. The downtime was determined by listing all events that occurred during deployment (e.g. run days, maintenance, external events) in chronological order and the timespan between each maintenance/external event and the next run day gives the approximate downtime of the system. This was deemed the most appropriate method to determine system downtime caused by maintenance and external events for a number of reasons: 1) it's very common to experience multiple maintenance/external events between each run days, 2) the exact downtime of an event is very difficult to determine due to the different numbers of personnel as well as multiple components that may be involved, and 3) maintenance events are highly affected by accessibility of parts, time of shipment, and labor availability.

The most frequent issues are related to battery start-up and inverter communication with the system, as seen in Figure 55. Of the 30 maintenance issues that occurred during the deployment period, 30% (9 occurrences) were related to the inverter while 23% (7 occurrences) were related to battery. The major issue with the inverter is failed communication with the overall system controller, which leads to a fault in the AC output of the system. Due to troubleshooting and repair/replacement, the inverter and battery also caused the largest system downtime at approximately 93 and 63 days, respectively.

The second most common issue that occurred during deployment was battery-related. Battery issues are categorized into two types: one related to the actual battery (root cause) and the other related to battery startup issues from the generator being idle for an extended period due to another component malfunctioning or an external issue. Long periods of system idle between runs (up to 1-2 months) typically resulted in low voltage output and a dead battery, leading to a downtime of 47 days in comparison with 19 days of downtime from the actual root cause of the battery. Due to the frequent start-up issues related to the battery, the battery was replaced towards the later phase of the deployment process, in March 2016.

Table 17: Summary of maintenance and issues

#	Component Name	Component Category	Maintenance Type	Downtime in Days	Date of Repair, Replacement	Operating Hours at Repair, Replacement
1	Hydrogen fitting	H2 Storage	Adjustment	2	10/5/16	113:18
2	Inverter	Inverter	Repair	31	10/19/15	114:07
3	Battery	Battery	Repair	29	10/21/15	114:07
4	DI Reservoir	Fuel Cell Coolant	Adjustment	3	11/10/15	114:07
5	Fuel Cell Container	Structural	Adjustment	3	11/10/15	114:07
6	Smoke Detector	Monitors/ Sensors	Adjustment	3	11/10/16	114:07
7	Coolant Thermocouple	Monitors/ Sensors	Repair	3	11/10/15	114:07
8	Radiator Fans	Glycol Coolant	Adjustment	3	11/11/15	114:07
9	Inverter	Inverter	Repair	3	11/10/15	114:07
10	Coolant	Fuel Cell Coolant	Adjustment	31	1/9/15	115:54
11	Fuel Cell Stack 4	Fuel Cell	Repair	31	1/9/15	127:51
12	DI Headtank	Glycol Coolant	Adjustment	1	2/10/16	127:51
13	Inverter	Inverter	Repair	3	2/13/16	151:16
14	Inverter	Inverter	Repair	6	2/16/16	152:30
15	Inverter	Inverter	Repair	9	2/23/15	153:01
16	Inverter	Inverter	Repair	8	2/24/15	153:01
17	Inverter controller	Inverter	Repair	3	3/1/15	153:01
18	Coolant	Fuel Cell Coolant	Repair	7	3/11/16	169:07
19	Battery	Battery	Repair	11	3/18/16	171:45
20	Hydrogen Tank	H2 Storage	Repair	1	3/29/16	177:38
21	Battery	Battery	Repair	1	4/7/16	213:50
22	Battery	Battery	Repair	9	4/12/16	214:00
23	Battery	Battery	Repair	9	4/13/16	217:14
24	Battery	Battery	Replacement	1	4/22/16	218:21
25	Hydrogen Tank	H2 Storage	Repair	4	4/23/16	218:49
26	Inverter	Inverter	Repair	1	4/27/16	227:24
27	Hydrogen Tank	H2 Storage	Repair	1	4/27/16	227:24
28	Inverter	Inverter	Repair	29	5/2/16	243:35
29	Fuel Cell Rack	Monitors/ Sensors	Repair	29	5/2/16	243:35
30	Battery	Battery	Repair	6	6/1/16	243:35

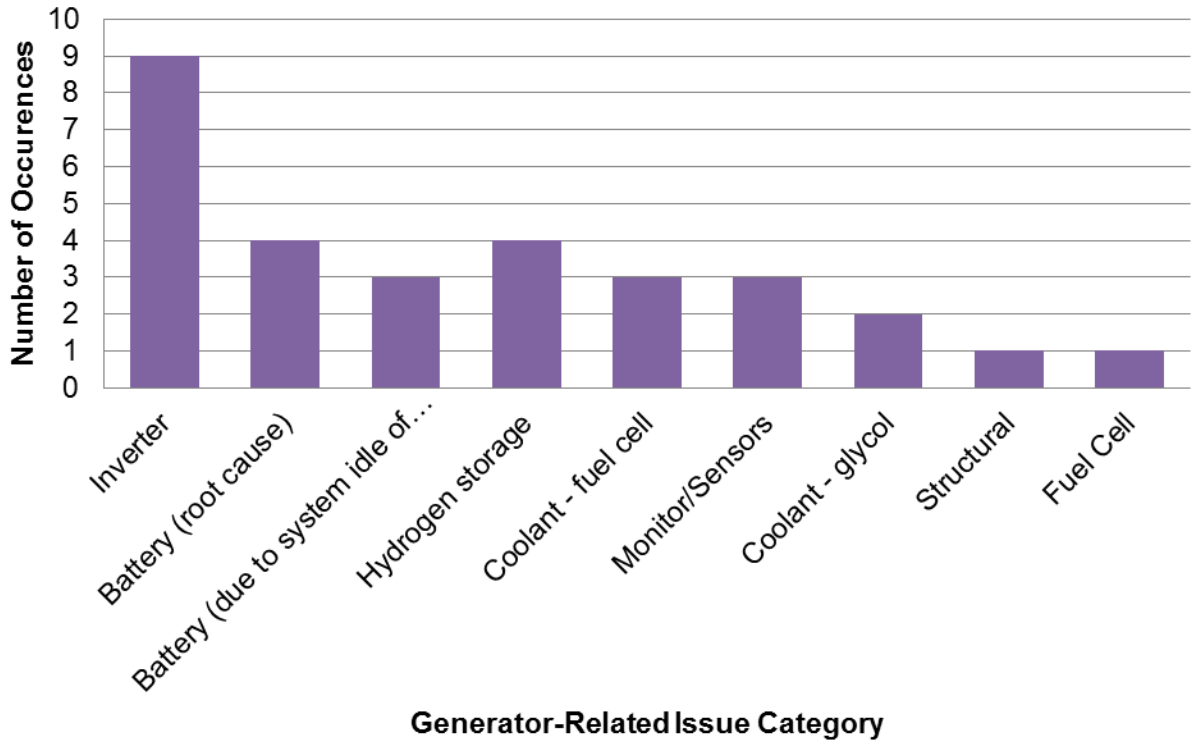

Figure 54: Generator related issues and occurrences during the deployment.

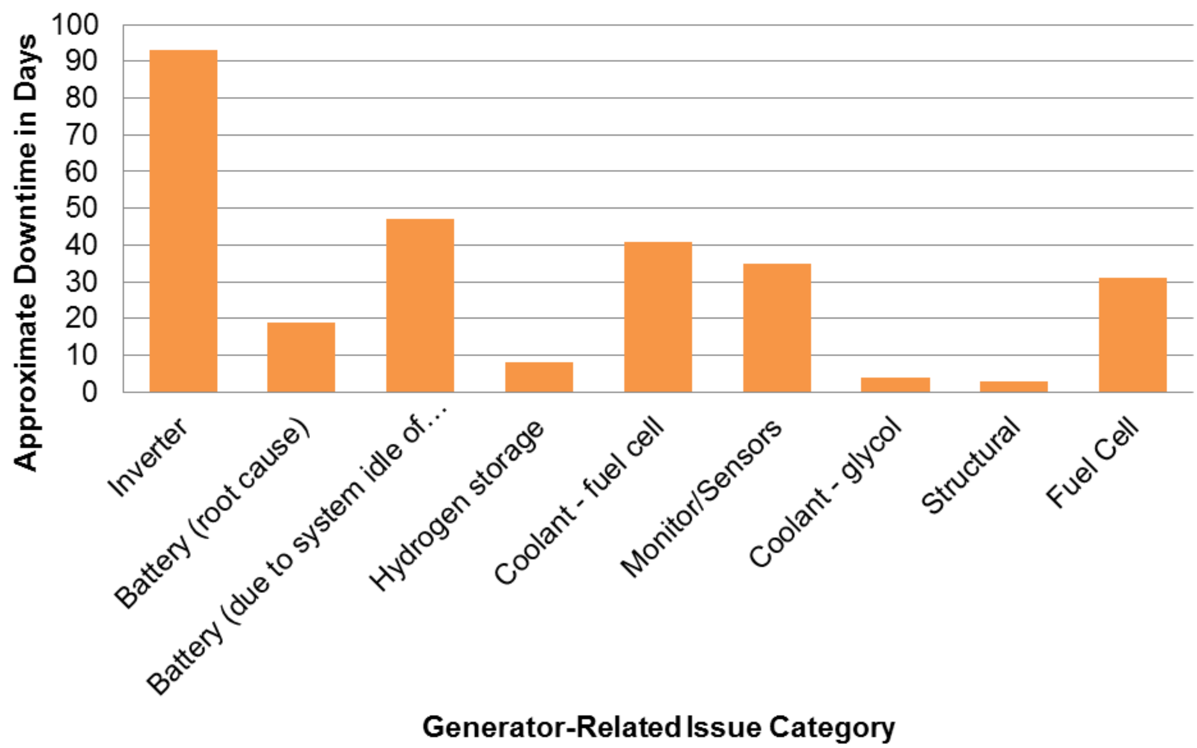

Figure 55: Generator-related components downtime during the deployment.

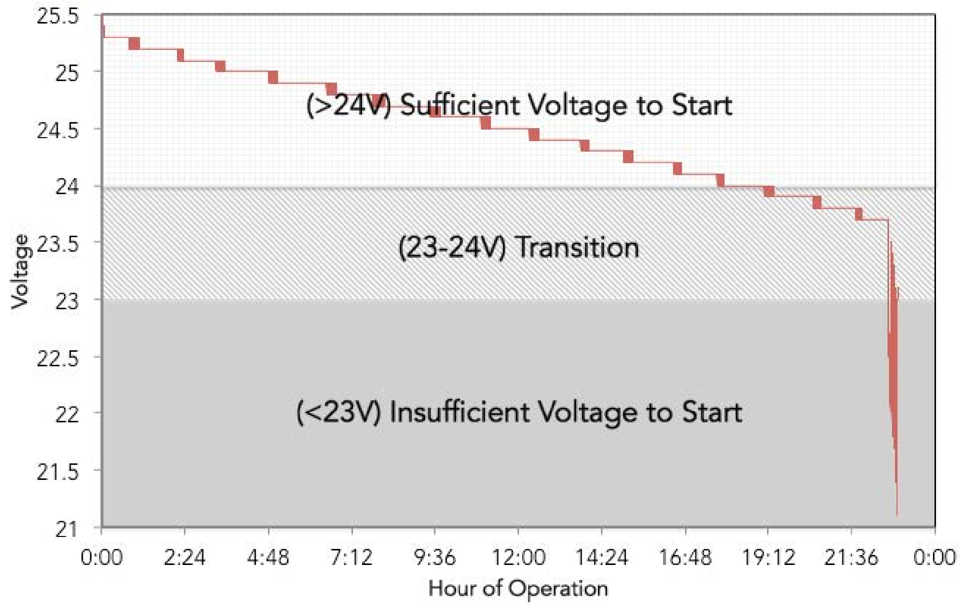

Figure 56: Startup battery voltage decline during H2-detect mode, and measured voltage ranges for successful startup.

It was found through examination of start and attempted start data that the battery voltage required to start the generator is higher than anticipated. Figure 56 shows battery voltage decline for a time period where the system was left in H2-detect mode for nearly 24 hours. In the figure background it can be seen the resulting action when the system is requested to start. Above 24 V the system always has enough battery power to start. Between 23 V – 24 V there was variable behavior – sometimes it would be sufficient and other times not. Below 23 V the battery was never able to start the generator. These voltage thresholds correspond to about 17 hours of allowable time in H2-detect mode to stay above 24 V, and about 5 more hours to stay above 23 V. The manufacturer is aware of the higher-than-expected battery voltage required to start and will perform corrective action to reduce startup power consumption from the battery in order to enable a wider range of acceptable battery voltages for startup.

Another issue that required regular maintenance was the fuel cell coolant (DI water) component. These issues included fuel cell coolant dropping below recommended operating level, high coolant temperature, and frequent refilling that led to several system start-up issues. Fuel cell coolant consumption was higher than expected during deployment in comparison with laboratory testing but shown by Hydrogenics analysis to be within normal levels. The fuel cell coolant caused the third largest downtime among all the components, at approximately 41 days.

5.3.2 External Issues

External issues are summarized in Table 18. External issues are problems outside of the fuel cell generator that occurred during the deployment period, which led to system downtime or additional expenses. They are divided into four categories, summarized below.

1) Labor/manpower: issues related to lack or shortage of staff and personnel (e.g. employee calling in sick) that led to system downtime or maintenance delays

2) Legal: issues related to contract and insurance that needs to be resolved before operating the unit
3) Logistical: other facility issues at Young Brothers (e.g. pier under construction, barge maintenance) that affected the generator operation
4) External: other issues such as those related to the hydrogen refueling station at Hickam that affected the generator operation

Table 18: Summary of external issues and resulting downtime.

Date of Event	Event Description	Additional Details	Downtime (approximate days)
9/28/16	High bar compressor at Hickam station breaks down		1
10/4/16	Operator attends labor negotiations	Operator gone 3-4 days/wk for 3-4 weeks. No one able to operate the unit consistently.	1
10/4/16	Operator vacation	Not enough manpower to monitor and operate the unit	1
11/24/15	Barge maintenance requiring operators to be reassigned		12
11/24/15	Operator 1 attends labor negotiations		12
11/24/15	Operator 2 attends interisland training	Cannot move forward without everyone on board	12
12/2/15	Insurance contract/agreement	YB cannot operate unit without liability agreement. Unit will not run until resolved	35
1/6/16	Barge inspection		1
1/10/16	Barge inspection		0
3/1/16	Pier under construction at stern berths P39 and P40	Space constraint/vehicle traffic issues, leading unit to be run at Ice House temporarily. Construction will continue for two weeks	1
3/1/16	Operator is out for a week	Unit can only be troubleshooted once he returns	3
4/21/16	Received battery replacement but electrician is out and there are some barge issue preventing installation for at least a week.		1

The most common external issues are related to labor and manpower, as shown in Figure 57, occurring a total of 9 times during the deployment period. Manpower and labor-related issues resulted in about 45 days of system downtime. These are primarily due to staff shortage issue related to construction at the pier, maintenance of other systems at the port, work-travel, or vacation. While legal issue related to insurance contract between Young Brothers and Sandia National Laboratory occurred once during deployment, it also led to significant system downtime (35 days), as shown in Figure 58.

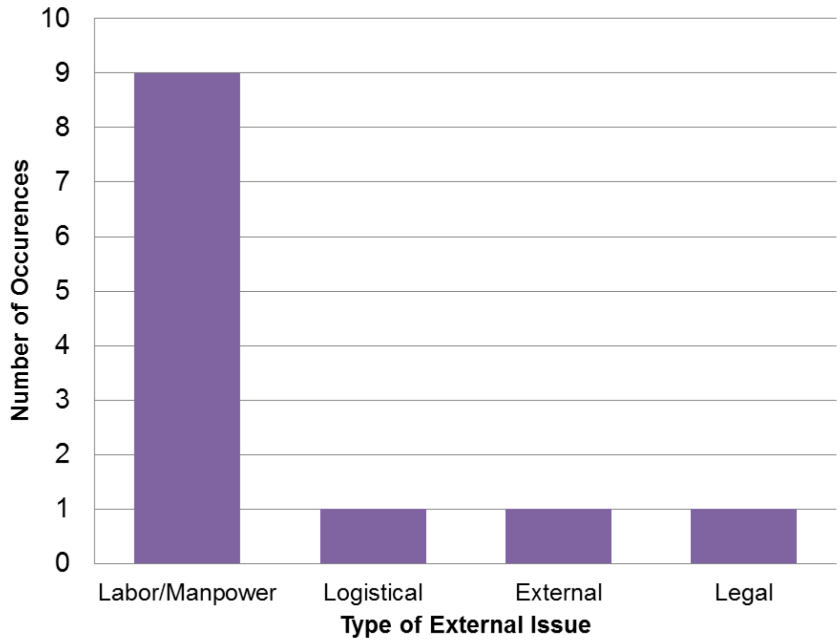

Figure 57: External issues and frequency.

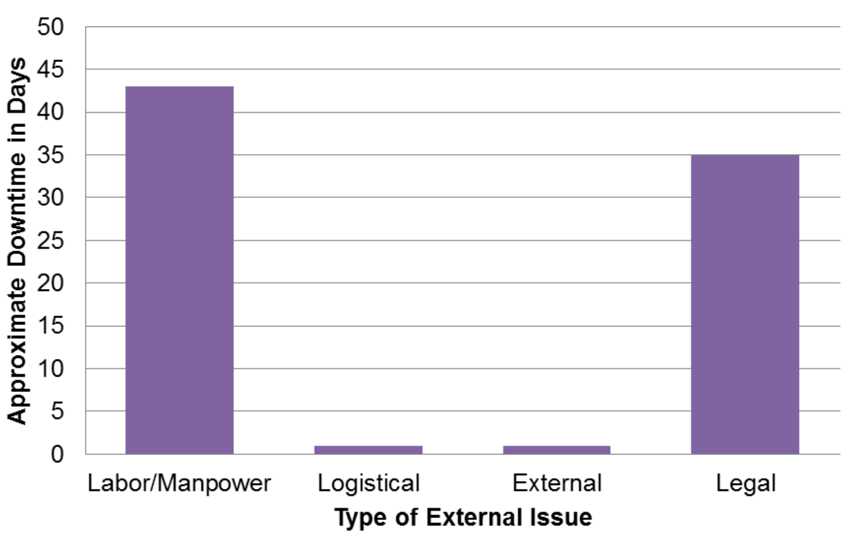

Figure 58: System downtime due to external issues.

5.3.3 Recommendations

A list of recommendations and improvements from the manufacturers, users, and others on the project team are listed below:

System-related

- Increase number of plugs on fuel cell unit to power more reefers (only 10 plugs on one unit). Diesel generators on site can power as much as 25 reefers.
- Use a lighter paint for the fuel cell container to deflect heat
- Use a more standard battery that is available locally for ease of replacement (difficult to find battery near site)
- Provide better feedback for the operator - the indicator lights on the generator currently provide no feedback on issues.
- Generator shuts down if one single fuel cell module shuts off. This is the result of a design decision two years ago and should be re-considered in future deployment to enable better resiliency.

Fueling-related

- Although not tested, on-site refueling seems like it would be preferred compared to offsite. On-site refueling is more familiar since it is what is done with diesel generators, and requires less manpower and coordination.

Logistical-related

- Assign/hire one staff dedicated to operating and maintaining the fuel cell unit. There is insufficient manpower as well as skill set to manage the fuel cell generator.

5.4 Effect of the Marine Environment

The effect of salt air and water/spray of the marine environment was observed during the deployment. Because the generator was not used over the water, it was not exposed to water or direct spray, but the humid Hawaiian air enabled some assessment of corrosion.

Figure 59 through Figure 62 show some examples of observed corrosion during the 9 months the generator resided at Young Brothers. It is limited to unpainted portions of the generator structure and sides. In addition, the use of mats on the floor trapped water and accelerated corrosion as can be seen in Figure 60. When discovered, the mats were removed and the floor re-done with a more durable paint. The optimal solution to corrosion prevention would be the use of an aluminum or stainless steel floor plate.

In accordance with recommendations from the Hydrogen Safety Panel, in April 2016 the high pressure piping was inspected both on the surface and under pipe clamps. Figure 61 and Figure 62 show some example findings. In general the corrosion was very limited and appears to be associated more with iron particles contacting the pipe in pinpoint locations rather than general corrosion due to the environment.

While more of a result of sunlight than the marine environment, some discoloration of the power buttons was observed, as shown in Figure 63. This illustrates the need for UV-resilient materials on future installations or inclusion of regular service/replacement of any fade-prone materials into the maintenance schedule.

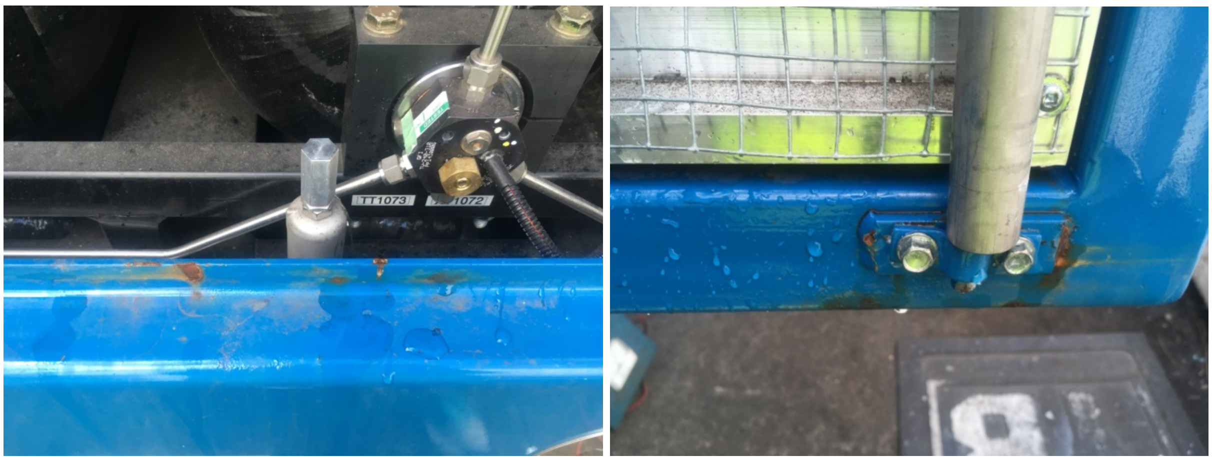

Figure 59: Some examples of corrosion on unpainted external surfaces.

Figure 60: Generator room floor corrosion due to continual presence of mats. Mats were subsequently removed and the floor was re-painted with more robust paint.

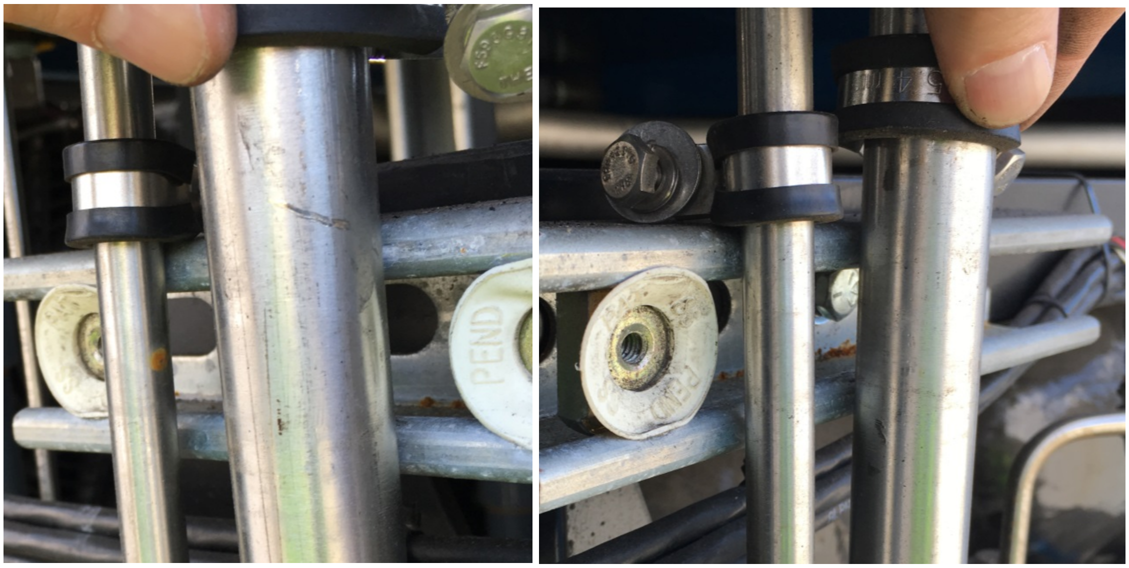

Figure 61: Inspection of stainless steel piping under the rubber pipe clamp. Only a small spot of corrosion was found after 9 months (left picture, left tube) and is likely due to a trapped iron filing rather than the salty air. The rust spot was easily removed by hand.

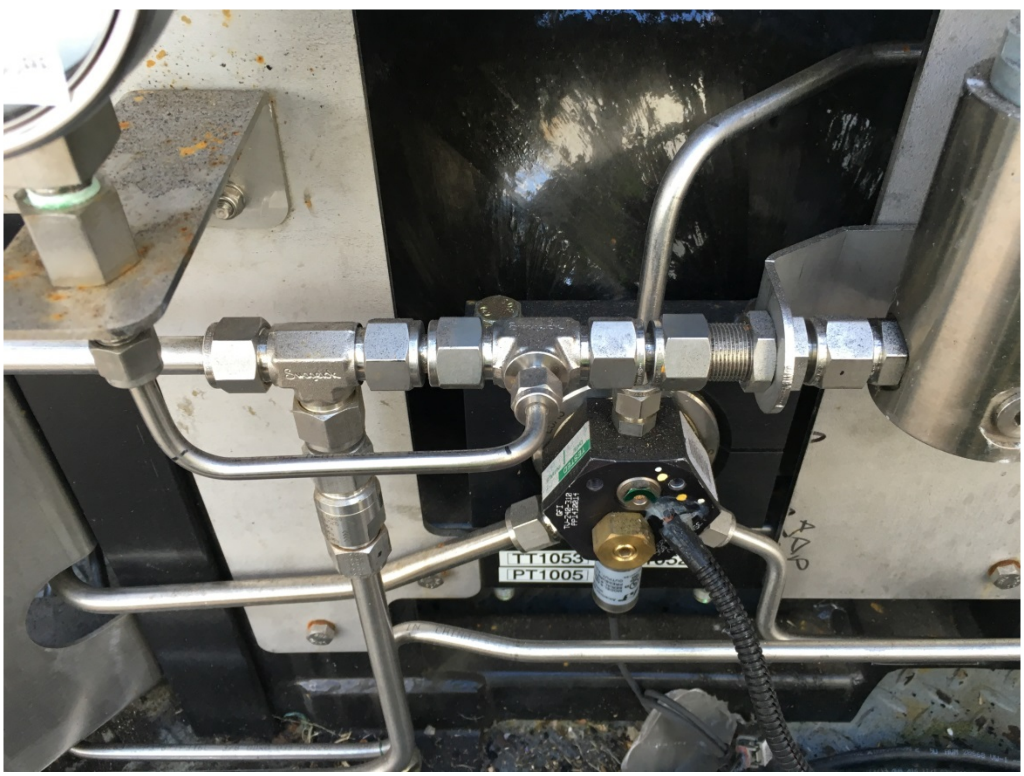

Figure 62: Some of the stainless steel piping inspected for corrosion after 9 months of deployment. Very little corrosion on the piping was observed.

Figure 63: Slight fading of generator control buttons due to sun/UV exposure.

6 Economic Evaluation

6.1 Capital Costs

The capital cost of the system include the cost of the fuel cell modules as well as any purchased or subcontracted balance of plant components such as hydrogen tanks, sensors, environmental system, cooling system, and other power-conditioning and electronic equipment. These costs represent direct manufacturing (or purchased parts for BOP) and do not include non-product costs such as sales and marketing, warranty costs, installation, shipping etc. The quote for a single-unit (or low volume) order of a 100kW HyPM-R generator today is $800-900K based on input from Hydrogenics. About 1/3 of the capital cost is the fuel cell power system (120kW gross power fuel cell stack = 4 x 30kW modules), and 2/3 of the capital cost is the balance of plant components. Inverters and hydrogen tanks are the major BOP drivers. This is primarily because inverters for the fuel cells come from solar suppliers, which are accustomed to supply chains of megawatts-scale solar farms and fuel cell systems at this stage are still considered low-volume. As the maritime fuel cell market develops, it is expected existing suppliers in the maritime space will produce cheaper power-conditioning and electronic equipment. Hydrogen tanks remain high because there are not many suppliers in the market and the volume is still relatively low. With the mass production of fuel cell automotive cars, it is expected the tank material and manufacturing cost will be reduced. .

Figure 64 shows cost-volume projections for a single order unit, 50 orders, and 100 orders or more. In general, there is about 15-20% cost reduction for an order greater than 50 units, and 10-15% additional reduction for orders greater than 100 units. Cost reduction comes primary from the inverters, hydrogen tanks and fuel cell stack. The fuel cell stack cost reductions are driven by the high volume stack manufacturing and MEA[10] materials due to high volume order from suppliers. There is very little cost-

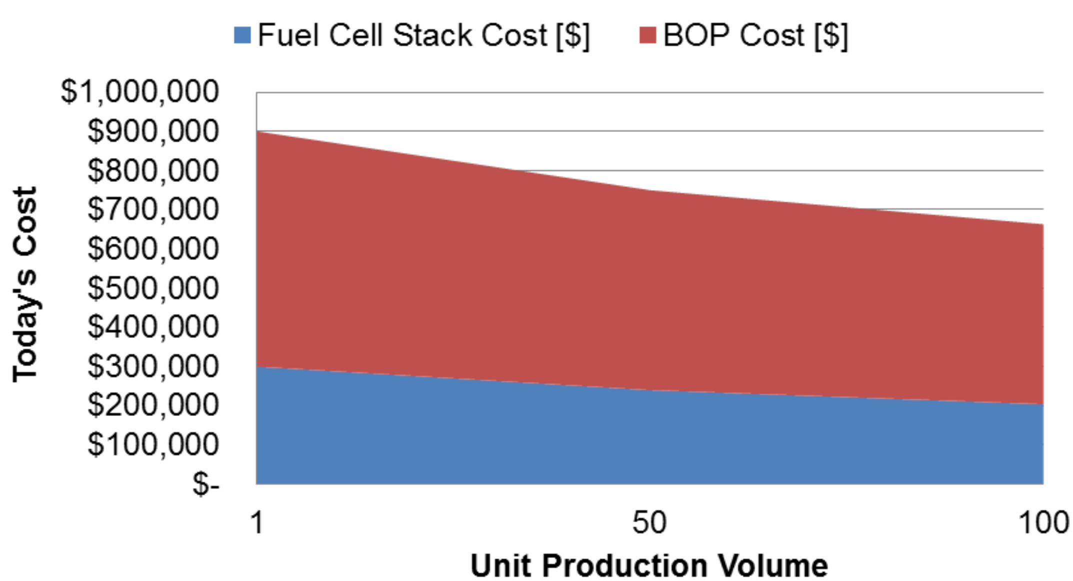

Figure 64. Cost-Volume Projection for Stack and Balance of Plant

[10] MEA: Membrane Electrode Assembly, consists of the membrane, gas diffusion layers, and bi-polar plates.

Table 19. Summary of cost-volume projection for a 100 kW PEM fuel cell system built today.

System Size [kW]		100kW	
Production Volume (Systems/yr)	1	50	100
Fuel Cell Stack Cost [$]	$300,000	$240,000	$204,000
BOP Cost [$]	$600,000	$510,000	$459,000
Total Cost	$900,000	$750,000	$663,000
Total [$/kW]	$9,000	$7,500	$6,630

volume reduction in the BOP because BOP components do not scale as well as the stack with volume (e.g. for a volume of fifty 100kW units, 4 x 120 cells/stack x 50 units (fuel cell modules) = 24,000 cells, but only 50 inverter and 800 hydrogen tanks are needed). Table 19 summarizes the cost figures for different volume production.

A 300 kW Tier 4 containerized generator system outfitted as required by Young Brothers costs approximately $300,000 ($1,000/kW). Scaling for comparison to the fuel cell generator, at $1,000/kW this translates to a cost of $100,000 for a 100 kW unit. Therefore, a single-order today of a hydrogen fuel cell generator has an $800,000 cost premium, and if a 100 unit order were placed today the hydrogen fuel cell generator would have a $563,000 capital cost premium.

6.2 Operating Costs

Operating costs are the expenses related to the system spent by the operator or manufacturer to maintain normal functioning of the system. Operating costs include the costs of fueling the generator and maintaining and monitoring the unit. This analysis does not consider the costs of the project team which would be considered un-necessary in a true commercial application, for example, data collection and analysis.

6.2.1 Cost of Fuel

For the Maritime FC deployment, the fuel was supplied from the hydrogen station at the Hickam Air Force Base. The hydrogen was provided free of charge from the Air Force (via HCATT) for this demonstration. The only refueling cost to Young Brothers during the deployment was the cost of trucking to/from the Hickam station. This cost averaged $240 per round trip, and there were eight refuelings where the generator received a total 480 kg (as described in Section 5.1.2), working out to a cost of $4/kg.

Outside of this specific deployment, the hydrogen itself is not expected to be zero cost. Recent estimates from industrial gas suppliers for supplying a six-month deployment of this generator at a port in California reveal delivered hydrogen costs between $15/kg and $30/kg. Different agreement terms (duration and quantity) have the potential to change the cost lower or higher. However, as shown in Figure 9 of Section 2.2, even a delivered cost of $10/kg would result in nearly double the diesel fuel cost if diesel is $4/gallon, and nearly triple when diesel is $2.50/gallon. Trucking the generator off-site to a retail hydrogen station for refueling would remove the delivery component of the cost but likely not result in any cost savings as retail hydrogen prices are currently $13-$15/kg.

6.2.2 Cost of Maintenance

Data collected during the deployment such as labor hours, rates, and nature of work were limited. The sporadic operating nature of the deployment was not conducive to the operators being able to establish a routine including keeping regular logs of maintenance time spent. In addition, it was difficult to distinguish between routine maintenance events and maintenance due to problems since it was the first time a system like this had ever been used. Thus it is not possible to quantitatively assess the differential maintenance cost of a fully-functional hydrogen fuel cell generator compared to a fully functional diesel generator. Qualitatively, the generator appeared to have similar preventative maintenance needs as a diesel generator in terms of time and effort when it was working correctly.

Hydrogenics' experience with mature containerized electrolyzer units, which have similar components inside, can give insight into expected routine maintenance costs. In their experience, a total annual scheduled and unscheduled maintenance budget is estimated to be about 1-2% of capital cost. For the hydrogen fuel cell generator, this results in an expected maintenance expense between $7,000-$18,000/year (depending on whether 1% or 2% is used and which capital cost from Table 19 is assumed). We assume that a Tier 4 diesel generator has a similar yearly maintenance expense, so the net difference in routine maintenance expense between the fuel cell generator and the Tier 4 diesel generator is zero.

This maintenance cost will not include major powerplant overhaul. After the fuel cell reaches its rated life, it must be refurbished at a cost approaching that of a new stack. According to Hydrogenics, this time before refurbishment can be between 10,000 to 15,000 hours.

Analysis of the YB operating profile of the current diesel generators assumes a total of 4,000 hours of operation per year. The current design of the generator distributes the load evenly among stacks, meaning that each stack will experience the full 4,000 hr/year. From Figure 2 this low load operation on the fuel cell can be seen to provide an efficiency advantage, lowering fuel consumption. However, the control system could be modified to limit the number of stacks in operation to only that needed to meet the load. Assuming a load profile of 1/3 time at 25 kW, 1/3 time at 50 kW, and 1/3 time at 75 kW, and considering that each stack is rated at 33 kW, it can be seen that nearly all of the time the load can be met while keeping one or more stacks in standby, which does not produce wear on the stacks and therefore does not count towards the replacement interval hours. If the system were operated in this way, each stack would see an average of 2,000 hr/year.

By contrast a single diesel generator is not able to proportion its load to reduce yearly operating hours and would experience the full 4,000 hr/year. Here we assume a well-maintained Tier 4 diesel engine will require one form of overhaul (top-end, bottom-end, complete, etc.) every 15,000 hours and the average cost of performing each overhaul was estimated to be 25% of capital cost.

The resulting 10-year lifetime costs are summarized in Table 20. A 10-year life for these generators in this service is average, according to Young Brothers, due to the harsh environment and handling conditions.

Table 20: Fuel cell stack replacement / diesel engine overhaul costs over a 10-year lifetime. Assumes 2,000 hours of operation per year for the fuel cell stacks and 4,000 hours of operation per year for the diesel engine and no fuel cell cost reductions from today's costs.

Type of Generator	Hours before fuel cell / engine overhaul	Number of overhauls in 10 years	Assumed FC replacement / overhaul cost*	10-year overhaul cost	Yearly overhaul cost premium compared to diesel
H_2 fuel cell	10,000	2	$300,000	$600,000	$55,000
H_2 fuel cell	10,000	2	$240,000	$480,000	$43,000
H_2 fuel cell	10,000	2	$204,000	$408,000	$35,800
H_2 fuel cell	15,000	1	$300,000	$300,000	$25,000
H_2 fuel cell	15,000	1	$240,000	$240,000	$19,000
H_2 fuel cell	15,000	1	$204,000	$204,000	$15,400
Diesel	15,000	2	$25,000	$50,000	$0

*Fuel cell replacement costs from Table 19.

Due to the similarity in regular maintenance costs observed qualitatively, the overhaul cost differential is the only contributor to increased maintenance costs of owning the fuel cell generator.

6.3 Future Cost Projections

Long term reductions in powerplant costs are expected as the fuel cell industry production volumes increase. For example, the US DOE predicts that mass manufacturing of fuel cell stacks can reduce costs to nearly $50/kW at the high volumes associated with large scale fuel cell electric vehicle adoption (500,000 x 80 kW units per year).[18] Such a drastic cost reduction would decrease the originally estimated fuel cell stack cost from $300,000 for a single unit to just $5,000 and with balance of plant cost reductions would make the capital cost of the generator equivalent or lower than that of the comparable diesel, and overhaul costs would result in a savings compared to a diesel generator. While this is a long-term proposition, it shows the cost reduction potential of fuel cells which can be contrasted against the trend of increasing costs of diesel engines due to more stringent emission regulations as discussed in Section 2.1. Since the generator uses PEM fuel cells, the power plant costs would directly benefit from cost reductions anticipated for PEM fuel cells used in light duty vehicles.

6.4 Societal Economic Benefit of Emission Reductions

This section assesses the cost of health and environmental externalities associated with fuel cells. Fuel cells can impose health and environmental impacts during the different stages of its life-cycle, from the extraction of raw materials for manufacturing, manufacturing of the stack, operation and use-phase, and the production of energy for its manufacturing, delivery, and servicing of the cell. However, the use of fuel cells can also offset the production of electricity in the region where the cells supply power. This offset can have health benefits depending on the sources of electricity in the region and the impacts associated with that electricity production.

The approach used to monetize emissions displaced by the fuel cell generator is the following: the fuel cell generator displaces some fraction of electricity demand that otherwise would come from a diesel generator. The benefit of emissions reduction by adopting a fuel cell system can be monetized using marginal benefit of abatement (MBA) conversion factors. Marginal benefit of abatement estimates the

Table 21: Emission factors for Caterpillar C15 350kW rated diesel generator (from interpolation)

Percent Load	g NO_x/kWh	g CO/kWh	g HC/kWh	g PM/kWh	mg SO_x/kWh	kg CO_2/kWh
25%	5.44	5.69	0.66	0.23	4.590	1.15
50%	4.73	4.09	0.27	0.13	3.945	0.93
75%	4.49	2.50	0.14	0.09	3.606	0.86
100%	4.37	0.90	0.07	0.08	3.384	0.82

health and environmental damages that a unit of emitted pollutant (SO_2, NO_X, particular matter PM) will cause in a specific geographic location, and hence are often being referred to by its alternative name "damage factors".[19] The potential damage from a pollutant emission from a given source is estimated by multiplying the mass of emitted pollutants by the MBA factor. Since the fuel cell generator uses pure hydrogen and generates no pollutant emission at the point of use, the emissions displaced is simply the emissions generated by the diesel generator at the same power output. The emission factors for NO_x, CO, HC, SO_X, PM, and CO_2 at different loads for a 300kW Caterpillar C15 diesel generator previously shown in Figure 45 are tabulated in Table 21 for selected load conditions.

There are a number of existing literature that estimates MBA factors, with the most widely referenced approaches found in Fann et al., Muller and Mendelson, and Machol and Rizk, which estimates the costs of human health and environmental impacts associated with different pollutants in the United States, as shown in Figure 65.[20-22] The average MBA factors ranged from \$1500 to \$80,000 per tonne SO_2, \$370

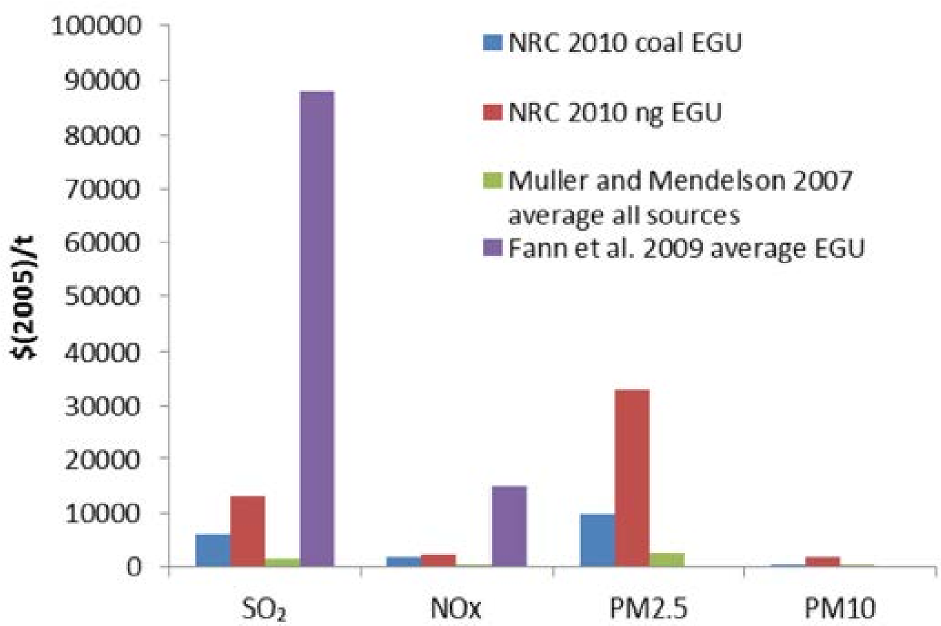

Figure 65: Marginal abatement factors for USA from different literature

to \$15,000 per tonne NO_x, \$2,700 To \$33,000 per tonne $PM_{2.5}$, and \$440 to \$1,800 per tonne PM_{10}.[23] The large variations in the MBA factors exist depending on the scope of the study (e.g. geographic location, urban versus rural areas), the atmospheric model selected, the type of pollutants included, and other database and model used to determine health damage and impact. For each model, various atmospheric chemistry models and transportation models are used to estimate downwind primary and secondary pollution doses from an original plume of pollutant. For example, oxygen atoms are produced from photolysis of NO_2 by the ultraviolet portion of solar radiation, and reacts with molecular oxygen (O_2) to form ozone (O_3). Exposure level is estimated from a database of receptor populations (humans, crops, materials, etc.) and concentration-response (CR) models converts exposure to damages. Economic models then convert the health impacts such as mortality, visibility impairment, reduced recreation etc. to dollar values.

The large variations in the MBA factor points to a number of uncertainties and challenges in tracking pollutants and determining their impacts. First, air pollutant cost-benefits assessments are largely dependent on geographic regions, and given the large scope it is difficult to characterize the behavior of a particular pollutant in a limited geographic area. Second, the formulation of certain pollutants such as $PM_{2.5}$ follows a non-linear chemistry process, and therefore capturing the physical process in the model is a complex and time intensive task. There are simplified approaches that offer computation efficiency but may introduce uncertainties. Furthermore, no damage factors database were available for the state of Hawaii. For these reasons, the MBA factors for this analysis were adopted from Fann et al. as it is the default approach used by the US Environmental Protection Agency (EPA). The EPA provides the most up-to-date values using a computer program called BenMAP[11] thus giving the best estimates for the damage factors. The marginal abatement factors for NOx, SOx, and PM are summarized in Table 22.

Greenhouse gases like CO_2, CO, and HC[12] were converted to CO_{2eq} using 100 year global warming potential (GWP) factors of 1, 10, and 26, respectively.[24] We assume a social cost of carbon similar to the method used by Wei et al.[25], which monetizes greenhouse gases using a social cost of carbon of \$44/ton $CO_{2,eq}$. In comparison to other greenhouse gases, CO has a small direct global warming potential but it can lead to indirect radiative effects. For example, the production of CO_2 comes from oxidation of CO which can lead to double counting of carbon dioxide. The emission of CO also affects OH which can in turn lead to an increase in the lifetime of CH_4. For all of these reasons, the GWP value for CO is subjected to many uncertainties. The GWP for CO can estimated with multi-dimensional box model. Table 23 shows that the 100-year GWP for CO is approximately 1.0 to 3.0, and 2.8 to 10 for the near-term from different studies. We used the GWP factor from Fuglestvedt et al. [26] for this analysis since it

Table 22. The economic value of a 1 ton reduction in directly emitted PM2.5 or PM2.5 precursor emissions from 19 sources in 2016 (in 2010 dollars) [27]

Sector	Nitrogen Oxides	Sulfur Dioxide	Particulate Matter
Electricity Generation Units	\$5,200	\$35,000	\$130,000

[11] https://www.epa.gov/benmap

[12] Such as methane (CH_4). Global warming potential for HC is calculated by taking the average of the different hydrocarbons data available

Table 23. Estimated indirect Global Warming Potentials for CO for time horizons of 20, 100, and 500 years

Study	Model	Indirect Global Warming Potentials		
		20 years	100 years	500 years
Daniel and Solomon (1998) [28]	Box model considering CH_4 feedbacks only	2.8	1.0	0.3
Fuglestvedt et al. (1996) [26]	2D model including CH_4 feedbacks and tropospheric O_3 production by CO itself	10	3.0	1.0
Johnson and Derwent (1996) [29]	2D model including CH_4 feedbacks and tropospheric O_3 production by CO itself	---	2.1	---

Table 24. Monetized marginal environmental and human health impacts avoided by the fuel cell generator for the deployment.

	Avoided Emissions	Societal Benefit
NOx	68.5 kg	$356
PM	5.1 kg	$663
SOx	2.3 g	$0.08
CO	56.3 kg	$25[a]
HC	17.8 kg	$64[a]
CO_2	16,400 kg	$722[a]
Total		$1,830

[a]The societal benefit of avoided CO, HC, and CO_2 is estimated based solely on global warming potential using the factors described in the text, not direct health effects.

uses a multidimensional model to capture both the direct and indirect behaviors of CO.

Table 24 summarizes the monetized marginal environmental and health impacts of the 100kW fuel cell generator compared to a diesel generator during the deployment when combining the social costs of emissions with the avoided emission amounts described in Section 5.2.4 (reprinted in the table for reference).

6.5 Economic Conclusions

For both the fuel cell and diesel generator, the total cost of electricity includes the generator capital cost, scheduled maintenance costs, and fuel costs, divided by the amount of annual electricity provided by the system. A net cost of electricity which considers the societal economic benefit can also be determined by subtracting the calculated societal benefit from the total cost of the fuel cell system.

Table 25 summarizes the economic analysis for the deployment and for projected full usage scenarios at today's costs and future projected costs. The input data are described in the footnotes as well as the preceding text in this chapter. Some observations can be made:

- The deployment enjoyed free fuel from the Hickam station, only paying for trucking, which is a large reason why the cost per kWhr of the deployment was lower than what is projected for full usage at today's costs.
- Even with fuel cell costs reaching the DOE target of $50/kW, the capital cost of the generator is projected to remain higher than a comparable diesel generator due to the balance of plant. Large portions of the balance of plant cost are the power conditioning (inverter) and hydrogen storage tubes. Cost reductions in both of these are necessary to enable competitiveness no matter how much cost reduction can be achieved in the fuel cell stacks.
- Fuel is the major yearly expense for these systems. While today's difference in hydrogen costs (high) and diesel costs (low) is expected to significantly decrease in the future, today it hinders the ability of fuel cell systems to achieve cost parity with diesel systems.

Table 25: Summary of economic evaluation of the 100 kW fuel cell generator for the deployment and projected full usage, with comparison to a notional 100 kW diesel generator.

	Hydrogen Fuel Cell			Diesel
	Actual Deployment	Full Usage & Today's Costs	Full Usage & DOE Target Costs[a]	Full Usage & Today's Cost
Lifetime (yr)	10			
Usage (hr)	278	4,000/yr		
Electricity Generated (kWhr)	7,285	200,000/yr		
Amortized capital	$3,278[b]	$90,000/yr[c]	$30,000/yr[d]	$10,000/yr
Maintenance	$660[e]	$18,000/yr		
Overhaul[f]	$4,170[g]	$30,000/yr	$5,000/yr	$5,000/yr
Fuel	$1,920	$177,000/yr[h]	$47,300/yr	$40,700/yr[h]
Total Electricity Cost	$10,028	$315,000/yr	$100,000/yr	$74,000/yr
Total Electricity Cost per kWhr	$1.38	$1.58	$0.50	$0.37
Societal Benefit	$1,830	$16,900/yr	$16,900/yr	-
Net Electricity Cost per kWhr	$1.13	$1.49	$0.42	$0.37

Table Notes:

[a]$50/kg fuel cell cost and $4/kg hydrogen fuel

[b]Assuming $900,000 purchase price amortized over 10 years and adjusted for the deployment ratio of kWhr produced (7,285 kWhr) versus expected kWhr at full usage (200,000 kWhr).

[c]Assuming a $900,000 purchase price

[d]Assuming stack and BOP cost reductions achieve cost parity with a 300 kW Tier 4 diesel at $300,000.

[e]Estimated for a correctly working generator based on $18,000/yr, and adjusted for the deployment ratio of kWhr produced (7,285 kWhr) versus expected kWhr at full usage (200,000 kWhr).

[f]Based on 15,000 fuel cell life, 2,000 hr/year of usage per stack and $300,000 replacement cost for the fuel cell (see Section 6.2.2); 15,000 time between overhaul, 4,000 hr/year of usage, and $25,000 overhaul cost for the diesel engine

[g]Full usage amount adjusted by the ratio of actual hours to full usage hours per stack (278:2,000)

[h]Hydrogen at $15/kg and diesel at $2.50/gallon

7 Conclusions and Recommendations for Future Development

7.1 Conclusions

The purpose of the Maritime Fuel Cell Generator project was to determine whether a self-contained hydrogen fuel cell system could replace a diesel generator to provide a reliable source of clean electricity on a commercially-competitive basis in a maritime application.

Through design and build of a prototype 100 kW generator it was found to be technically possible to do so with a design that is safe to operate. The inherent high part-load efficiency characteristics of fuel cells were verified illustrating the advantages to replacing diesel power generation when the generators are frequently operated at part load (as is typically done). Rapid fueling of the generator's 70 kg capacity hydrogen tanks to 350 bar proved to be a straightforward and trouble-free process showing that large amounts of hydrogen can be transferred quickly which can enable adoption of hydrogen-powered equipment in other applications.

The data collected and projections for full-usage deployments indicate that cost reductions in fuel cell technology, balance of plant items, and hydrogen fuel can result in cost parity with diesel generation. Of these three items, fuel cell cost reduction seems most feasible while additional effort is recommended to reduce hydrogen fuel costs and balance of plant components, especially power conditioning and hydrogen storage. The cost reductions necessary to achieve parity depend on the deployment location since fuel and technology costs differ around the world.

While the cost reduction requirements are clear, the limited operating time of this demonstration did not produce enough data to complete a quantitative assessment of how hydrogen fuel cell technology can compete with diesel engine power generation technology. In particular, more information is needed on maintenance needs, usage logistics, and longer-term fuel usage as compared to diesel generators. This can be obtained by further demonstrations in a commercial environment as a diesel generator replacement. Such demonstrations at a port can also allow assessment of ports as "hydrogen hubs", that is, a place where hydrogen is used for multiple commercially viable applications while at the same time allowing leverage by the surrounding area for introduction of hydrogen fuel cell vehicles.

As the first demonstration of a self-contained hydrogen fuel cell generator at a port, this project showed that it is possible to reduce maritime-related emissions through the use of hydrogen fuel cells and identified paths forward to more widespread adoption of the technology in the marine sector.

7.2 Recommendations and Lessons Learned

Testing over 10 months by the host identified several areas of needed technical improvements to enable adoption, which can be incorporated into this generator as well as subsequent products. A list of lessons learned are during the course of the deployment is summarized below. Many valuable lessons were learned during the course of this demonstration that are applicable to 1) similar maritime demonstration projects in the future, and 2) to general hydrogen and fuel cell technologies.

Lessons applicable to similar demonstration project

- External issues outside of the technical issues of the fuel cell generator, such as those related to labor, logistical, and legal matters can impact the operation of the fuel cell significantly
- Fuel cell container should be painted in a light color to avoid overheating of the unit in a hot and humid environment such as Hawaii. High temperatures in the generator room can lead to overheating of the system, startup issues, high DI water usage in the stack, and faster coolant evaporation rate
- Fuel cell enclosure needs to be raised higher to avoid forklift damage to the bottom of the container
- Most reoccurring technical issues are not related to the fuel cell but instead to balance of plant components such as the battery and the inverter. These components should be carefully assessed before future demos.
- Logistical issues at the port such as those related to inspections, constructions, labor shortage, etc. are issues that impact generator operation. Unit operation would increase if one staff is assigned to operate and maintain the fuel cell unit in future demonstrations until the technology becomes as trouble-free as its diesel counterpart.
- Reefer and checkout logs needs to be maintained regularly to keep track of generator usage

Lessons applicable to H2/FC technology in general

- The fuel cell needs to be run regularly - long idle-periods lead to start-up issues, coolant evaporation, and greater maintenance time
- Hot weather environments such as that experienced in this project can potentially affect a fuel cell system's performance. High temperatures lead to higher than expected evaporation through the vent in the tanks, leading to high DI water usage
- During fills, some of the integrated tank fill valves seemed to require more than 30 psi and some up to around 200psi to open (refer to fill analysis Section 5.2.6.4). High opening pressure can result in tank temperature swings during fill higher than the fault condition and cause system timeout. Temperatures should be monitored during the fill to determine if there are any issues with tanks not being filled, and more consultations with the manufacturer should be conducted to understand the cause of these wide variations and possible solutions to manufacturing or application.
- Balance of plant components, especially power conditioning equipment and hydrogen storage tanks, need to achieve cost reductions similar to those projected for fuel cells in order for hydrogen fuel cell systems to become cost-competitive with diesel generation technology.
- Trade-off studies are needed to assess differences between using inverters to supply AC power for AC motors versus converting AC motors to DC to enable simpler DC-DC conversion or direct drive from the fuel cell system. The inverters and ultra capacitors represent significant costs and size/weight additions. Such a study should consider the many variables involved such as cabling, power requirements, maintenance, etc. The resulting optimization should help to close the cost gap between diesel and fuel cell technology.

Lessons applicable to this generator

- More run time is needed to determine effects of environmental conditions on operational characteristics
- There should be one staff dedicated to running and managing the fuel cell generator for the unit to be operated more - it is very difficult for Young Brothers personnel to manage and run the fuel cell generator in addition to their existing job duties
- Increase the number of outlets on the fuel cell unit so that it can power more reefers (current diesel generators on site can power as much as 25 reefers). This would require increasing the power production and fuel storage possibly leading to a 40' container size, but that trade-off may be an acceptable one if it achieves usage requirements.
- Consider a more streamlined fueling procedure in future deployments - the hydrogen tank truck loading/unloading is inefficient compared with the diesel fuel tanks that are on site
- Use more standardized BOP components with more local availability for ease of replacement (e.g. it was difficult to find replacement battery from local suppliers due to the particular specs)
- The indication lights on the unit need to provide better feedback to the operator. Currently, they do not give any information on the system's fault when flashing.
- The hydrogen mass during refueling from the data logger on the unit does not accurately represent the actual amount of hydrogen in the storage tanks since it is calculated based on ambient pressure but the pressure is higher during refueling. The data logger should be corrected in the next deployment.
- Consider adding a DC-DC converter to power off the ultra capacitors to charge the 24V startup battery. The battery would be getting charged even in ultra-cap mode and it would limit the charge current during operation. A diode would have to be installed between the battery and power supply so that the power supply doesn't directly charge the battery.
- Water from fuel cell exhaust drips down the doorway and can lead to corrosion issue. This is an original design issue, changing the exhaust louver orientation and adding an internal drain in future designs may help alleviate this problem.
- The fuel cell generator shuts down if any single fuel cell module shuts down. This is a result of a design decision from the manufactures and may want to change with diodes so that one fuel cell module shutting down will not shut down the whole system after the deployment.

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Appendix A

Hydrogen Safety Panel review of the Maritime Fuel Cell Generator Project, including description of resolution of comments by the Project Team

HYDROGEN Safety Panel

PROJECT REVIEW

Design Review of the Maritime Fuel Cell Generator Project
July 14, 2014

Background

At the request of the Sandia National Laboratories, the Hydrogen Safety Panel (HSP) members Farese, Scheffler and Frikken participated in a review of the Maritime Fuel Cell Generator Project. This is the second project review performed by the Panel and is based on updated project documentation, including changes to address comments provided during the preliminary design review in May 2014.

Results and Comments

General Project Comments

1. Some clarity on the strategy for tank standard selection could be beneficial. For example:
   a) NGV-2 tanks are likely to be safe, but will the project be subject to regulatory scrutiny?
   b) It's not clear that the project could transport the container on public roadways utilizing NGV tanks filled with hydroen using NGV tanks.
   c) PHMSA certified tanks are safer and may be a better choice.

   The project should consoder connecting with DOT for a formal interpretation regarding the rules for portable, non-vehicular applications. Information on this topic could be beneficial not just for this project but future applications.

   The project will use the following strategy and rationale for the hydrogen storage tanks. This approach has been agreed upon by DOT (Quon Kwan, Federal Motor Carrier Safety Administration):

   1. The design and operation of the prototype is considered to be comparable to that of a commercial fuel cell vehicle and not of a hydrogen storage system. The only reason for our system to store hydrogen is for its immediate use, not for transfer to any another system, and its only interface to other hydrogen equipment is for refueling purposes; same as with a fuel cell vehicle. In effect, it is a "fuel cell bus without wheels" that can be trailered or carried to a location to conduct refueling operations.
   2. This is consistent with the fact that NFPA 2, which governs hydrogen storage systems, specifically excludes "onboard vehicle or mobile equipment components or systems, including the onboard GH2 or LH2 fuel supply." In other words, NFPA 2 also considers mobile equipment such as this to be functionally equivalent to vehicles and not subject to the same regulations as those which govern dedicated hydrogen storage systems.
   3. To meet DOT requirements for any time when the prototype will be transported over the road, the prototype will be designed to meet the "Guidelines for use of hydrogen fuel in commercial vehicles" published by DOT in November 2007.
   4. Compressed gas tanks designed, built, and tested according to NGV-2 meet the requirements of the aforementioned guidelines (Section 3.1.1, paragraph 4) and are appropriate for this piece of equipment.

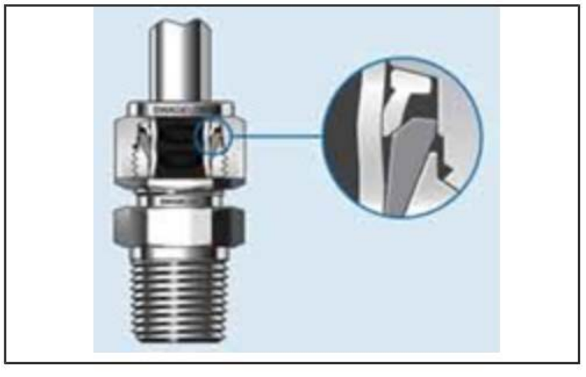
<u>Note added February 2017 with publication of the report:</u> The original approach is included here without modification for reference. US DOT and the Hydrogen Safety Panel should be consulted prior to considering this approach in other efforts. Refer to report Section 4.4.3.1 for clarifications on the approach described here.

2. The project is a bit of a hybrid between DOT and ASME type applications and it also appears that the ventilation system will not be operational at all times when the tanks contain hydrogen. Therefore, hydrogen detection should be provided in the storage compartment and configured to shut the tank valves if activated.
   (NOTE: The issue falls into a gray areas as the project want to utilize vessels that are typically used for vehicle applications (NGV), but look and feel more like industrial cargo. Tube trailers would not have gas detection, but they also ship with all valves tightly closed. Operating vehicles tend to have gas detection, partly since the valves are open when moving. All of this implies that it would be prudent to include gas detection in the gas storage area, similar to a car or bus, since the valves will normally be open while in transit [i.e. operation]. It's also effectively an indoor area despite the semi-open construction. And, the concerns about chloride cracking increase the potential value of a detection system. However, if the storage compartment exhaust system is operational at all times when the valves are open then the need for detection may not be critical.)
   The open-wall and slanted roof nature of the hydrogen storage compartment mitigates the effect of potential hydrogen leakage and hydrogen detectors will be used in the (closed) fuel cell compartment. Additionally, a marine grade hydrogen detection system has since been added to the design in the Hydrogen storage room. In the event a leak is detected all valves will be closed. Addiitonally the system is instrumented with multiple pressure transmitters on both the high and low pressure sides and automated leak checks based on decay rates will be conducted at each system shutdown (every 1-3 days) to detect for any possible leaks.

<u>Tubing Corrosion Assessment Plan</u>

Overall the corrosion assessment is well researched and written, and provides steps in the right direction. The Panel questions two points made in the assessment:

1. Relying on the 60 C is a fairly tight threshold. Will either sun-baked temperatures come close to 60C?
2. It seems like the ferrules in Swagelok fittings still must take the material past yield. Otherwise, there won't be the "strong grip" described in the illustration from the Swagelok catalog.



During assembly of the advanced-geometry design (above), the front ferrule is driven into the fitting body and the tubing to create primary seals, while the back ferrule hinges inward to create a strong grip on the tubing. The back ferrule geometry allows for an improved engineering hinging-colleting action that translates axial motion into radial swaging action on the tube, yet operates with a low assembly torque requirement.

For example, if there is a fitting with the nut oriented up as illustrated above, salt spray will settle in the groove against the outside seal. The water will evaporate leaving the salt. The chloride concentration will continue to increase at that location. The stress may be near the yield strength at that location because the high stress is needed to create the “strong grip”. Two necessary conditions are satisfied, but the temperature may well be below the susceptible range.

Overall, the probability of failure of the tubing caused by chloride stress corrosion cracking is likely very low, but not zero. As noted in the assessment, these tubing systems are used in this environment in many different services with an apparently acceptable failure rate. If the project would like to reduce the risk further, then sealing the space between the nut and the tube with silicone caulk could work well. The only problem with this approach is that keeping the seal over the long term is problematic. However, that may be acceptable for a short-term demonstration project.
Swagelok has indeed noted that tube stress in a properly-made joint in the area behind the back ferrule (can be exposed to seawater through the nut bore) can be in the vicinity of and potentially exceed the typical yield stress of SS316L tubing (25 ksi). Sandia has concluded that while the precise critical stress level needed to enable stress corrosion cracking depends on other variables such as chloride concentration and temperature, it is reasonable to assume that stresses near the yield stress could satisfy this condition.

The use of sealants has been shown to be problematic as they are prone to imperfections which cause exposure and then the resulting area has even less exposure to oxygen, increasing the susceptibility to crevice corrosion.

The design does not have any areas that will be subject to > 60 C. The louvered wall (open but shaded) nature of the hydrogen storage compartment helps to ensure this, considering the average high temperature in Hawaii is 31 C. Within the compartment, tubing fittings are be spaced at least 5 cm from the ducts carrying the warm fuel cell exhaust air. In addition, ambient temperature measurements will be made in multiple locations within the container that will trigger alarms in the event the internal container temperature exceeds 50 C.

As noted in the section above, the system will implement automated leak checks on shutdown and hydrogen detection to ensure that in the event a leak does occur it is detected and the system is safely shutdown.

<u>Design Review: Maritime Fuel Cell Generator Project PowerPoint</u>

1. Slide 3 – Has DOT been engaged to provide interpretation of the applicable tank standard? Yes, see first question above.

2. Slide 5 – Is the storage system ventilated from two sides or just one? The end with the radiators and one side that appear open, but on slide 6 the other side appears to be closed. Are louvers used as "splash guards" on the sides?
   One side and the end. Double-angled louvers are present on the ends and the sides and act as splash guards.
3. Slide 8 – Has the applicabilitiy of DOT requirements (49 CFR) been considered?
   Yes, see above.
4. Slide 8 – The cited NGV-2 standard is probably adequate for this application, but the basis for the comment relative to HGV-2 is not clear. HGV-2 is harmonized to the FCV Global Technical Regulation (GTR) under WP29 of the UN. Some people might think that having a UN regulation constitutes a significant degree of "adoption." As an example, much of the GTR tank requirements were based on SAE J2579 for vehicular hydrogen systems and considered issues related to adiabatic heating in tanks with hydrogen.
   Noted.
5. Slide 9 – Has the frame for the mounting brackets also been designed to withstand 8g?
   The mounting frame has been designed to withstand 6g load in each direction. A linear analysis and FEA report will be provided by a third party engineering firm to validate the design. The frame has been designed out of 2"x2"x1/4" thick steel and will be painted with marine grade paint. Gussets are used at all corners for bracing.
6. Slide 9 – MPP-350-8 Valve – Is this manual, automatic or both?
   Manual. However, the design has been changed and instead of this manual valve one automated tank solenoid valve will be used per tank,TV-240-310. This valve has an integrated manual shutoff as well as an integrated PRD, thermistor, and pressure transmitter port.
7. Slide 9 – Are thermally-activated T-PRDs provided on each end of the tanks? What are the chances of fire from the end with radiators such as electrical motor fire or what about fire exposure from the generator room? Are there PRDs to address these possibilities, if credible, particularly near the center of the tanks (far away from the PRDs on the ends of tanks)? Note: SAE J2579 and the GTR address localized fire situations in addition to the "engulfing bonfires" addressed in NGV-2.
   Both ends of the tanks have thermal PRD's set at 109 C
8. Slide 10 – What failure do the temperature and pressure-activated PRDs address?
   This is addressed in the FMEA (under internal review)
9. Slide 12 – What is the purpose of the flow restricting orifice? What are the maximum flows through the orifice over the operating range 100-5,000 psig?
   The flow restricting orifice limits fill speed in order to maintain acceptable temperature levels in the tanks during fill. The maximum flow rate for the fill port is100-120 g/sec (7.2 kg/min max). To put this into perspective, this is a maximum flow rate of 9.6% of the tank system's capacity per minute. In actuality the process will be slower as the supplying tank truck will interrupt the process due to the need to switch tanks for cascade fill. 350 bar vehicle tanks are typically fueled at greater than 20% of their capacity per minute without interruptions. Thus the temperature rise in the tanks should be much less than is currently accepted for tanks applied to vehicle service.

The WEH filling receptacle specs are TN1, 350 bar, H2, 10mm, HF, 40um, model C1-94306.

10. Slide 12 – Has the impact of adiabatic heating during "fast fills" been addressed?
    See above.
11. Slide 14 – Will the extended roof be removed during transport to prevent damage?
    No. The slanted roof is welded on the inside of the cargo container's roof and will not be exposed to something that can cause damage.
12. Slide 15 – 5th bullet – Does this paragraph refer only to fuel cells, or also to fuel storage compartments?
    This slide refers to the fuel storage compartment.
13. Slide 19 – Does the fan create a positive pressure for the room area relative to the atmosphere surrounding the storage system?
    The exhaust fan pushes air out of the generator room creating a negative pressure inside the room. With this configuration any small leaks would be directed out of the room through the ventilation system so that leaks can be easily detected. With a positive pressure system the concern is that leaks would be made to circulate the room and not follow a direct path out of the room.
14. Slide 22 – P&ID does not match page 11 showing other tanks.
    a. No flow restricting orifice shown (is there an excess flow valve instead?).
    b. Where is the second PRD (end plug design show earlier)?
    c. Is the regulator integrated into the tank valve or a separate component?
    d. At what location does the piping penetrated into the fuel-cell compartment (to help understand the boundary limit).

    An updated P&ID is in preparation.
15. Slide 24 – Why is UL1741 used as the apparent base standard? UL1741 primarily covers interconnection issues but not necessary with electrical or other safety issues within the inverter or electrical system themselves? Perhaps the project shoud consider utilizing CSA FC1, the Interanational Electrical Code or another more relevant UL standard?
    This is the standard the inverter manufacturer designs its equipment to comply with.

<u>Strategy Document</u>

1. Page 1, Hydrogen Storage Tank – A few questions on the tanks:
    a. What is the expected fill strategy and will it necessitate shipping over the road as effectively "cargo"?
       The project expects the tanks to be filled at the Young Brothers site, i.e., not transported for refueling.
    b. What is the DOT's interpretation of the appropriate tank standard in this service, considering that it's not providing motive power AND might be shipped on a public roadway in a non-functioning mode?
       See answer to top question.

2. Page 1, Hydrogen Storage Tank – If a solenoid valve is not installed on each tank will the PRD still be installed? If the solenoid is not installed, will there still be a manual valve for shutoff as would be required by 49 CFR for DOT approved cargo transit?
   One automated tank solenoid valve will be used per tank,TV-240-310. This valve has an integrated manual shutoff as well as an integrated PRD, thermistor, and pressure transmitter port.
3. Page 1, Hydrogen Storage Tank – Coast Guard regulations for transportation of flammable gases (e.g. what are setback requirements, loading requirements) were generally discussed during the May meeting. However, it is not clear that that the existing Coast Guard regulations for "fuel" address hydrogen. Are there regulations for compressed natural gas that can be applied?
   On-board the barge separation distances and regulations for this application are still being investigated.
4. Page 2, Hydrogen Storage Tank, 1st bullet – It may be beneficial to identify the operating requirements from the corrosion white paper here as well.
   Noted
5. Page 2, Electrical, Wiring, and (Internal) Hazardous Zone Classifications –How has the Class 1, Division 2 requirements of NFPA 70/497 been applied to the container location (including within 15 ft. of exhaust and openings from compartments containing hydrogen storage or equipment)? It may be beneficial for the Hydrogen Safety Panel to review this assessment.
   Operational separation distances for this application are still being investigated.
6. Page 5 provides the statement, "Canada now also accepts NGV cylinders produced to NGV2 2000." For what service is this referring to?
   This refers to hydrogen service.
7. Page 5, Pressure Cycling – Have these fatigue cycle pressures been modified for the 5,000 psig rating?
   The cylinder design will be subjected to 5000 psi fatigue cycle testing at the Luxfer facility.

Appendix B

Design Basis Letter from the U.S. Coast Guard

U.S. Department of Homeland Security

United States Coast Guard

Commandant
United States Coast Guard

2703 MLK Junior Ave., SE
Washington, DC 20593-7509
Staff Symbol: CG-ENG-3
Phone: (202) 372-1352
Fax: (202) 372-1925

16703
September 10, 2014

Sandia National Laboratories,
Attn: Mr. Joseph Pratt, Ph.D.
Project Manager, Maritime Fuel Cell Generator Project
Livermore, California 94550

Ref.: (a) "Maritime Fuel Cell Generator Project" presentation of June 19, 2014
(b) "Maritime Fuel Cell Generator Design Strategy" document of June 23, 2014

Dear Mr. Pratt:

We have reviewed the preliminary design documentation, including References (a) and (b), regarding the proposed temporary fuel cell installation to be installed on an unmanned freight barge currently in service in Hawaii. The purpose of the fuel cell is to provide electrical power to containers on the barge, and the fuel cell installation will, on a trial basis, temporarily replace the diesel-generator currently in use.

Reference (a) is an overview of the proposed installation, including the general arrangement of fuel cell mechanical and electrical components. Reference (b) is a detailed listing of applicable engineering standards to be used in this installation.

Enclosure (1) is a list of the standards applicable to this installation, and a summarization of the standards outlined in Reference (b).

The following engineering system plans and documents should be submitted to the USCG Marine Safety Center (MSC) for review of design compliance with the standards listed in Ref. (b):

(1) Hydrogen storage and distribution system, including tank and piping
(2) Ventilation arrangement for containerized fuel cell
(3) Non-hydrogen piping
(4) Electrical wiring and hazardous zone classifications (certified by a classification society or Professional Engineer)
(5) Fuel cell rack
(6) Failure Modes and Effects Analysis (FMEA). The FMEA should address the potential failures of the systems listed above, and the automated response of the fuel cell safety systems to mitigate the associated risks.

This letter serves as a general acceptance of the design concept for this particular fuel cell installation. Traditionally, the Code of Federal Regulations (CFR) for ships, in Titles 46 and 33 CFR, specifies engineering systems requirements based on the type of the vessel. The requirements and USCG oversight generally increase proportional to the size of the vessel, the number of passengers carried, and whether or not the vessel is engaged in the transport of hazardous cargo. All other regulations applicable to the barge's current certificate of inspection (COI) must continue to be met to the satisfaction of the Officer in Charge, Marine Inspection, Honolulu. Arrangements for hydrogen fueling, and additional crew and facility worker training regarding hydrogen handling should be coordinated with the Captain of the Port.

The CFR currently has no specific regulations regarding fuel cell installations. We hope that this trial installation and the associated design standards can help the USCG, vessel classification societies such as ABS, and other organizations such as IMO, develop standards and policies specifically applicable to fuel cell installations. Thank you for your efforts in helping to bring a renewable energy source to the maritime sector.

Sincerely,

R. W. MARTIN
Acting Chief, Systems Engineering Division
U. S. Coast Guard
By direction

Enclosure: (1) DOE – MARAD Fuel Cell Design Standards for use on Unmanned Barge

Copy: CG Marine Safety Center
CG Sector Honolulu
U.S. Maritime Administration (Attn: Mr. Sujit Ghosh)

Enclosure (1) DOE – MARAD Fuel Cell Design Standards for use on Unmanned Barge

Hydrogen Storage Tank
Code/Standard:
NGV-2 certified for use with gaseous hydrogen
Description:
The hydrogen storage tanks are Type 3 tanks (aluminum liner with carbon fiber overwrap) designed for 5,000 psi (350 bar) hydrogen gas. They have a service life of 15 years and a water volume of 205 L, which results in 4.96 kg of hydrogen capacity at 5,000 psi. The maximum pressure allowed by the tanks (may be reached during fills) is 6,345 psi and the operating temperature range is -40 °C to +65 °C. The tanks will be constructed and certified in accordance with ANSI NGV-2, pressure tested to 7,614 psi, and have a minimum burst pressure of 14,600 psi.

Fifteen (15) tanks will be installed in the prototype in five rows of three tanks each. Each row of tanks will have either a single solenoid shutoff valve, or each tank will have its own solenoid shutoff valve that are fail-closed and will be hardwired with the emergency stop circuit. Each solenoid valve contains an integral pressure relief device set at the maximum operating pressure of the tank. Each tank will be outfitted with a thermal relief device set at 102 °C.

Hydrogen Piping
Code/Standard:
ASME B31.12
Description:
The hydrogen piping will be in accordance with ASME B31.12, the Hydrogen Piping and Pipelines standard. High pressure hydrogen lines will connect all fifteen tanks in a manifold arrangement and the pressure will be reduced in the hydrogen compartment to 100 psig. Both a pressure relief valve and pressure switch hardwired to the emergency stop circuit protects the low pressure tubing from regulator failure. Low pressure hydrogen lines will feed into the power compartment and supply the fuel cells in parallel through two series connected UL solenoid valves. Each fuel cell contains another pressure regulator to the fuel cell required pressure of 5 psig. Each fuel cell contains an additional pressure switch and pressure transmitter to protect the fuel cell from failure of the 5 psig regulator.

High pressure hydrogen tubing and fittings will be SS316L.

Non-Hydrogen Piping
Code/Standard:
ASME B31.3
Description:
The non-hydrogen hydrogen-containing tubing and piping, primarily that used for cooling water, will be designed and built in accordance with ASME B31.3, the Process Piping code.

Electrical, Wiring, and (Internal) Hazardous Zone Classifications
Code/Standard:
NFPA 70 (the National Electric Code) Article 500 Hazardous (Classified) Locations, Classes I, II, and III, Divisions 1 and 2, UL 508 (Standard for Industrial Control Equipment), ANSI/ISA 12.12.01, and UL 913.

Installation evaluated by internationally-accredited field equipment inspection body QPS Evaluation Services Inc.

Description:

The cited codes will be used for the wiring installation as well as for any electrical components not covered specifically by other codes below. This includes design and installation as well as hazardous zone definition and classification.

In general any hazardous zone classification in the hydrogen storage compartment is avoided by making the compartment open to the atmosphere and not providing any pockets where hydrogen could accumulate; this assessment is done in accordance with NFPA 70. In the power compartment, hazardous zone classification is avoided through active ventilation, where flow rate will be determined in accordance with NFPA 70 and is expected to exceed 100 air changes per hour. The exception is upon system start, where two redundant Class 1 Div. 1 hydrogen detectors will be used to check for the presence of hydrogen in the compartment before any other (non-classified) electrical equipment is allowed to be energized.

Fuel Cell Rack

Code/Standard:

FC1 and UL compliant

Description:

The fuel cell rack will consist of four 30 kW Hydrogenics fuel cells, with a raw, DC power output of 120 kW, and will be designed to FC1 and be UL compliant. Each fuel cell will be equipped with integrated over-pressure switch, dedicated supply solenoid, and dedicated pressure transmitter. Each fuel cell will be fully leak-checked on build and will have built-in self leak check capability.

Inverter

Code/Standard:

UL 1741, ANSI 535, NFPA 704, and IEEE 519-1992

Description:

The DC-AC inverter will be designed for UL 1741 compliance and conform to signage requirements of ANSI 535 and NFPA 704. Inverter will be functionally designed for IEEE 519-1992 (IEEE recommended practices and requirements for harmonic control in electrical power systems) and IEEE 1547-2003 (R2008) (IEEE Standard for Interconnecting Distributed resources with electric power systems). The inverter contains two dedicated DC input channels with built in circuit breaker and pre-charge circuitry. It has 120kW, 240Vac, 3P-Y output with built in circuit breaker set at 350A. The unit has air cooled power electronics for -10 C to 40 C operation. The capacitor channel has a discharge current limitation of 170 Amps and no ramp rate limitation and the charge current limitation is configurable and will be set at 50A.

Lead Acid Battery for Startup

Code/Standard:

UL-508 listed and CE certified, conforming to IEC 61056-1, JIS C 8702-1, and GB/T 19639.1

Description:

The system incorporates two small HR33-12-B1 (31 Amp-Hour, 24V) valve-regulated lead acid Batteries (VRLA) for startup power. The sealed, maintenance-free, VRLA technology means that there is no hydrogen venting.

Ultracapacitor

Code/Standard:

IEC 60068-2-6, IEC 60068-2-27, and IP54

Description:

The ultra-capacitor system will be water resistant as per IEC 60529 – IP54. It will meet vibration specification IEC60068-2-6 and shock specification IEC60068-2-27, and -29. The ultra-capacitor system will have undergone substantial safety testing by the manufacturer including physical abuse testing, over-voltage testing, short circuit testing, and flammability and heat testing and in no case did the testing result in either fire, flame, or explosion. The ultra-capacitor voltage will be monitored while the system is being operated to ensure operation is well within specifications of the manufacturer (charge/discharge current, charge/discharge voltage, temperature). Each of the 3 series elements in the system will have their module voltages monitored so as not to exceed 150V and the system will be fused at 170 Amps and system shutdown will occur if deviations

Appendix C

Frequently Asked Questions about the *Containerized Fuel Cell Generator Operational Overview and Hydrogen Safety Training*

Frequently Asked Questions about the *Containerized Fuel Cell Generator Operational Overview and Hydrogen Safety Training*

Alarms, Emergencies and Procedures

Q: What constitutes an "emergency" or not?

A: Emergency conditions are:

- Smoke or fire in or around the unit (different from vapor from the exhaust vent during operation, which is normal)
- Loud hissing/whooshing noise
- Severe damage or impact
- Hydrogen detection horn sounding

The following are NOT emergencies but should be investigated:

- Reefers not getting power
- Coolant leaking onto the ground
- Fluids leaking on the ground when not in use
- Squealing or grinding noises
- Fails to start, no indicator lights
- Significant container damage or holes

Q: What is the communication procedure in case of emergency, i.e., a notification tree?

A: For emergencies contact:

1. Local fire department (or USCG if at sea)
2. Young Brothers supervisor
3. Hydrogenics (the manufacturer)
4. Sandia National Laboratories

Q: Will Knox box be keyed so either port (HFD or MFD) can access?

A: Although a Knox Box was previously intended, there will be no Knox box on the unit. The door is secured with a padlock which can be cut with boltcutters if entry is needed. Our feedback from first responders was that the simplicity and universality of bolt cutters is preferred to finding keys and manipulating a Knox box, especially in the case of multiple jurisdictions. YB will keep the padlock keys in a designated place.

Q: Where is alarm horn for smoke alarm and hydrogen sensors? Are sounds unique – can they be differentiated? How loud are they?

A: The horn is above the operator panel, which is above the reefer plug outlets. The sound is the same regardless of whether it is a smoke or hydrogen detector that triggers. The horn volume is up to 101 dB at 10 feet.

Q: If H2 sensor alarms (horn), how does one know if it is from storage or generator room?

A: To determine the reason for the horn the user will need to look at the online interface (<http:// 166.139.185.236 >). In addition, this condition will trigger an E-STOP, and an automated email with the reason will be sent to the contacts on the notification list.

Q: Can Coast Guard access information from overall system controller (OSC) if alarms sound or major accident occurs?
A: Coast Guard contacts can be added at their request to the automatic email notification system which will send an email in the event of E-STOP, Fault, or Alarm condition.

Safety Features
Q: Does the generator have lock out/tag out capabilities? How can the user determine if it's not to be operated?
A: To lock out the generator:

1. Shut it down normally
2. Press one of the ESTOP buttons INSIDE the generator room (there is one on the inverter cabinet and one on the electrical cabinet).
3. Lock the generator room door and apply a lockout tag (or follow normal lockout notification procedure).

Q: Is the container using double-wall pipe?
A: The container is not using double-wall pipe. The use of single-wall pipe for this application has been reviewed by the USCG, ABS, and the Hydrogen Safety Panel and none of the reviewers objected to single wall pipe when considering the application and multitude of other safety features.

Q: Are coolant radiator fans "Explosion Proof" or "Intrinsically Safe" as defined by the National Electric Code (NFPA 70)?
A: No. While the fans (or motors) are not Explosion Proof or Intrinsically Safe, safety is ensured through hard-wire lock outs in case any hydrogen is detected in the hydrogen storage room (where the fans are located). If hydrogen is detected on generator startup the fans will not be energized. At any time during operation if hydrogen is detected, power to the fans is immediately cut off via a hardwired switch.

Q: Who is responsible for container inspections, especially fuel tanks?
A: It is the project team's understanding that USCG has jurisdiction over the generator once it is deployed on the barge. Tanks have a certified lifetime of 20 years and the manufacturer recommends an inspection interval of 36 months (or anytime there is possible damage or fire). This interval is beyond the timeframe of the deployment and thus no need for inspections is anticipated, although the USCG is welcome to inspect any time.

Q: Generator labeling is on sides, and could (will) be obscured by other containers. Can graphics (e.g. DOT labels) be added to ends?
A: Blue diamond decals indicating on-board compressed hydrogen are on the ends.

Q: Diesel tankers and some diesel equipment are placarded. Why not the hydrogen fuel cell generator?
A: Placards indicate transport, not usage, of hazardous materials. Similar to your car or truck, and other pieces of industrial equipment that contain fuel such as diesel generators (including those at YB), light boards, lighting towers, etc. there are no US DOT requirements for placarding during use or transport. The project team has received authorization from the US Department of Transportation's National Highway Transportation Safety Administration to treat this generator in the same way. Although this equipment is not subject to hazmat segregation requirement because it is not cargo, YB has decided to segregate out of an abundance of caution for this first-ever demonstration.

Handling and Use

Q: Will the unit be placed on a platform to allow handling by a forklift?
A: Yes. Fork pockets on the unit itself have been blocked off, but the unit will be mounted on a dedicated platform.

Q: Can other containers, flat racks, etc. be stacked on top?
A: Yes. The fuel cell generator is designed enable stacking.

Q: Can the unit withstand starting up with the reefers plugged in and 'on', or will it send it into a fault? (with the plungers all punched in and reefers in the start position- can it take the load?)
A: This operation will be verified during commissioning. The generator is designed so that reefers can be plugged in, in start, with plungers punched in at any time. The generator has the ability to handle start-up loads from multiple reefers at the same time.

Q: Are there to be labels and simplified instructions on the user interface? Will there be a sticker that shows what lights mean near control panel?
A: A simple set of operational instructions and interpretation of the lights will be available near the control panel.

Design Features

Q: Are lights on user interface LEDs or filament with backup? If filament, can light burnout and system still run?
A: The lights are LEDs. If the light fails the unit will continue to operate, but an alarm will be triggered with automatic notification email.

Q: What is the durability and reliability of things like external switches, especially considering the effect of the salt on them?
A: All exposed components have been sourced for outdoor weather exposure and, when available, for marine-specific applications.

Q: Is there a local status indicator of 24V battery charge? How long before it runs down?
A: There is no local status indicator of the battery charge. To determine the charge of the 24V battery the user will need to look at the online interface (<http:// 166.139.185.236>). In addition, when the

battery level drops below 20 V, an alarm is triggered and an automatic email message is sent to the contacts on the notification list. At 16 V, a fault is triggered and the unit will shut down (and an email will also be sent). It is estimated that a fully-charged battery can power Hydrogen Detection Mode for approximately 100 hours (4+ days).

Q: Cargo arrives after an interisland voyage with heavy coating of salt from spray. Sometimes waves break over sides of vessel and “splash guards” may be ineffective. What would be effect of salt spray in generator room?
A: The generator room has a salt water filter on the air inlet that has been tested against extreme wash conditions and meets IEC 60068-2-52 which satisfies USCG and ABS requirements. See video demonstration of the filter at: https://www.youtube.com/watch?v=JyvXngnzbTU. If any salt water penetrates into the room it will drain out the floor. The fuel cells are protected from ingesting salt water or salt fog through additional chemical filtering.

For additional questions please contact:
Joe Pratt
Sandia National Laboratories
(925) 294-2133
jwpratt@sandia.gov

Appendix D

Final Report: Maritime Fuel Cell Project Hydrogen Safety and Emergency Response Training

Honolulu, Oahu and Kahului, Maui – Hawaii

A report by Monte Elmore, Pacific Northwest National Laboratory

[NOTE: This report has been modified from the original version submitted to Sandia. Attachments A and B have been modified to show slide thumbnails instead of full slides, and Attachment F has been deleted to protect the privacy of training attendees]

PNNL-24327

Final Report: Maritime Fuel Cell Project

Hydrogen Safety and Emergency Response Training

Honolulu, Oahu and Kahului, Maui – Hawaii

April 2015

Monte Elmore
Pacific Northwest National Laboratory
Richland, WA

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California Fuel Cell Partnership
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Acknowledgements

The authors wish to thank the following individuals for their cooperation and assistance in the delivery of this training:

- Joseph Pratt, Sandia National Laboratory for his efforts in coordinating this training as one of the many tasks under his overall Maritime Fuel Cell Demonstration Project.
- Training Captains: Scott Seguirant (Honolulu Fire Department) and Rylan Yatsushiro (Maui Fire Department) for their assistance in coordinating the schedules for their staff to participate in the training, and Captain Yatsushiro for providing the class room for training in Kahului.
- Nami Ohtomo, Young Brothers Shipping, for her assistance in coordinating Young Brothers staff that attended the training and for arranging use of the training room at the YB facility in Honolulu.

1. Introduction

A “National Hydrogen and Fuel Cell Emergency Response Training” program has been developed at the Pacific Northwest National Laboratory (PNNL) with funding from the US Department of Energy’s Office of Fuel Cell Technology. This training program focuses largely on hydrogen fuel cell-powered light duty private and commercial vehicles and stationary facilities, and has been presented to first responder organizations throughout the states of California, Hawaii, and Washington.

PNNL was contacted in 2014 by Sandia National Laboratory (SNL) to inquire about the possibility of adapting the “National Program” training to a maritime fuel cell (MarFC) demonstration project that was to take place in Hawaii in 2015. The scope of the MarFC demonstration project is to evaluate the adaptability of hydrogen fuel cell technology to a marine environment, specifically through deployment of a hydrogen fuel cell generator unit supplying electrical power to refrigerated shipping containers. Deployment of this generator unit would be between ports in Hawaii via barges over a six-month period. The barge company is Young Brothers Limited (YB), a subsidiary of Foss Maritime, based in Honolulu, HI. Figure 1 shows at barge being loaded at the YB Honolulu Facility. Figure 2 shows a typical diesel generator set used by YB to provide electrical power to refrigerated shipping containers. Figure 3 shows the hydrogen fuel cell power demonstration unit under construction that would replace a diesel generator set.

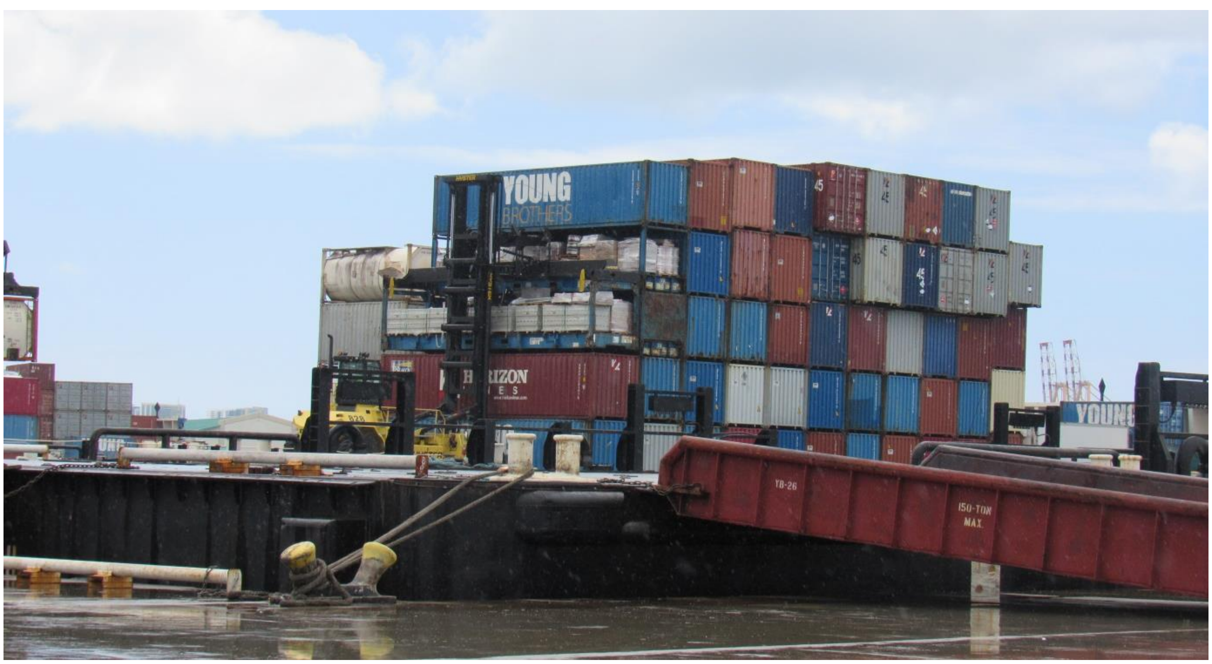

Figure 1. Young Brothers barge being loaded with a variety of shipping containers at the Honolulu facility.

Figure 2. Typical diesel generator sets used to provide electrical power to refrigerated shipping containers at dock side and in transit between islands.

The PNNL project to develop the training for the MarFC project was established in November 2014. The "National Program" was adapted for the MarFC project following a series of conference calls between SNL, PNNL, CaFCP, and YB personnel to identify likely attendees and to clarify the scope of information to be presented. Two locations for the training were selected: Honolulu, Oahu and Kahului, Maui. A preliminary list of attending organizations, shown below, was established and contacts with them were made to identify compatible dates for the training.

Honolulu, Oahu (Young Brothers Facility)	**Kahului, Maui (Maui Fire Department)**
Honolulu Fire Department	Maui Fire Department
Young Brothers, Honolulu	Young Brothers, Kahului
US Coast Guard, Honolulu	US Coast Guard, Kahului
Resolve Marine	
Clean Islands Council	
US Dept of Transportation - Harbors	

Some of the above organizations did not attend the training. Other organizations not on the preliminary list did send representatives. A complete listing of actual attending organizations and numbers of individuals from each organization is given in Section 3 – Training Statistics. The daily attendee rosters are given in Attachment E.

Section 2 – Training Outline provides an overview of the presentations given at each of twelve separate training sessions. Two presentations were prepared and presented during the training sessions: a) a project overview [provided by Joe Pratt, SNL] intended primarily for YB personnel, and b) a presentation covering hydrogen and fuel cell basics, hydrogen generation, transport and storage, fuel cell applications, and emergency response to hydrogen incidents with emphasis on this maritime project. Figure 3 shows Jennifer Hamilton (California Fuel Cell Project) presenting to attendees at the YB-Honolulu facility. The complete PowerPoint presentations are given as Attachments A and B to this report.

Figure 3. Jennifer Hamilton (California Fuel Cell Project) presenting the project overview to attendees at the Youn Brothers Honolulu facility.

The project desired training personnel close to but before the anticipated arrival date for the MarFC demonstration unit in Honolulu. Based on early planning discussions, the unit was expected to ship from Canada and arrive in Honolulu in early May. Therefore, training was targeted for mid to late April.

The fire departments were expected to have the most personnel at the training sessions. Therefore, training sessions were established around the availability of the fire department personnel. Each fire department [Honolulu Fire Department (HFD) and Maui Fire Department

(MFD)] operates with three shifts (A, B, and C shifts). With their shift rotation schedules, A B & C shifts are infrequently on duty on consecutive days. Working with the training captains from each fire department, potential training dates were identified where HFD had consecutive A B & C shifts on April 9, 10, and 11, 2015, and MFD had consecutive A B & C shifts on April 15, 16, and 17, 2015. Early estimates of attendance indicated there may be as many as 100 personnel per day (from all organizations) in Honolulu with lesser attendance in Kahului. Smaller class sizes were felt to be more effective, so two sessions per day were planned for each location.

Suitable training facilities were sought for the Honolulu and Kahului sessions. It was decided for the Honolulu training to hold the sessions at the YB facility's training room near their dock. This location was fairly centrally located for HFD crews coming from nearby stations. (These were the stations that would respond to an incident at the YB facility.) For the Kahului training, sessions were held at the MFD training facility located at their main station in Kahului (See Figure 4). YB-Kahului did not have an available training room large enough for the expected class sizes, whereas MFD did.

Figure 4. Maui Fire Department Headquarters - Kahului location of hydrogen safety training sessions on the Island of Maui.

Previous hydrogen emergency response training, from which this program was largely derived, had included demonstrations with a simulated passenger vehicle "burn prop". This burn prop was a ~3/4 scale model of a passenger car equipped to burn propane in the interior (simulating a compartment fire) and to burn hydrogen released through various vent locations around the exterior of the vehicle. This prop was fabricated for the purpose of allowing first responders to see differences between hydrogen and typical hydrocarbon-fuel fires, and to practice victim extrication from the vehicle while hydrogen was venting and burning.

A hydrogen burn prop was not planned to be included as part of the MarFC training. However, Mitch Ewan of the Hawaii Natural Energy Institute (HNEI), a participant in this project, had seen a demonstration given by Paul Ponthieux, CEO of Blue Planet Research (Island of Hawaii, HI), using a small burner fueled by hydrogen, and felt that the demonstration would be well worth including in this training. Paul Ponthieux was contacted and was very willing to support this training effort by supplying the small burner and bottles of hydrogen, enough for a short demonstration at each of the sessions at both training locations (see Figure 5).

Figure 5. Small gas burner adapted for hydrogen and used to demonstrate hydrogen flame properties to training attendees.

Additionally, SNL developed and provided two summary sheets to be handed out to attendees at the training sessions. One, titled “Hydrogen Fuel Cell Demonstration Project at the Port of Honolulu”, is a general overview of the project. The second handout, titled “Safety Features Integrated into Design and Use of System”, is a summary of general safety features built into the MarFC demonstration unit, and operational safety controls to ensure safety of operations personnel. These two handouts are included as Attachments C and D to this report.

2. Training Outline

As mentioned before, two presentations were planned for each session: the first an overview of the MarFC project, followed by a more detailed presentation on hydrogen, fuel cell, and emergency response. The overview presentation discussed the objective of the project, the scope and schedule, the partners involved, and described some of the details of the equipment. The overview presentation is given in Attachment A.

The second presentation, titled "Hydrogen and Fuel Cells Emergency Response Training for Sandia/Young Bros. Maritime Demonstration" (Attachment B), included the following sections:

- Introduction and Background – This section introduces the user to an overview of the role of fuel cells and their benefits, a picture of today's hydrogen production and delivery, current markets for fuel cells, and a diverse set of fuel cell transportation applications

- Hydrogen and Fuel Cell Basics – discusses basic properties and behaviors of hydrogen, how hydrogen compares to other fuels, how a hydrogen fuel cell works, potential hazards with hydrogen that may differ from those of other fuels, and the controls commonly used to assure the safe use of hydrogen

- Hydrogen fuel storage – explains compressed hydrogen storage systems, types of cylinders, and cylinder qualification testing and safety

- Containerized Hydrogen Fuel Cell Generator – describes key technical specifications of the MarFC demonstration unit, system overview, system controller functionality, system safety, system components, routine operation, and Emergency Stop feature. NOTE: this information was based on available information from Hydrogenics (the demonstration unit manufacturer contracted by SNL) at the time.

- Stationary Facilities – discusses types of stationary facilities, bulk transport and storage of hydrogen, stationary hydrogen fuel cell applications, components and configurations of a hydrogen fueling station, and safety features of a stationary facility

- Managing Hydrogen-related Emergencies - discusses potential hazards associated with hydrogen, and describes potential emergency response actions

The presentations were conducted informally. Questions and comments from the attendees were encouraged. In general, questions were limited, and attendees seemed satisfied with the amount and detail of information presented. A list of some of the questions and comments voiced by attendees is given in Attachment E. The US Coast Guard personnel showed considerable interest in the project, and asked some of the more insightful questions. Fire department personnel (and especially the Honolulu Fire Training Captain, Scot Seguirant) appeared to be satisfied with the emergency response information on hydrogen, and on their ability to deal with a hydrogen incident. Questions from YB personnel were generally about dockside operations, refueling operations, and barge loading concerns, as might be expected. Some questions could not be answered at the time they were asked in any particular session, and had to be deferred to later when specific information on design or operation could be verified with Hydrogenics.

The hydrogen flame demonstration was well received. In Honolulu the demonstrations were given out doors. HFD personnel brought thermal imaging cameras that helped to visualize the hydrogen flame. In Kahului the demonstrations were given in the classroom. (The first demonstration was given by Paul Ponthieux, and based on his previous demonstrations, satisfied the fire department that the demonstration would be safe indoors.) In the darkened classroom one could more easily see the faint hydrogen flame.

Nami Ohtomo arranged to have a complete training session recorded (video and audio) to assist in follow-on training of YB operations personnel. The recording was done on the second day of training at Honolulu.

3. Training Statistics

Each of the classes was well attended, averaging 28 per session in Honolulu and ~10 per session in Kahului, with a total of 225 for the two locations. The following table gives the number of attendees from each participating organization.

	Day 1 - 4/09		Day 2 - 4/10		Day 3 - 4/11		
ORG	am	pm	am	pm	am	pm	Total
Honolulu Fire	22	24	13	17	24	15	115
Young Brothers	10	4	1	3	1	2	21
US Coast Guard	3	2	10	4			19
HCATT	1	1	1				3
Servco			2				2
Clean Islands Council			7				7
ABS					1		1
	Day 4 - 4/15		Day 5 - 4/16		Day 6 - 4/17		
Maui Fire	9	11	6	7	9	7	49
Young Brothers	3		1				4
US Coast Guard			3				3
Blue Planet Research	2						2
							226

The rosters of session attendees are provided in Attachment F.

Attachments

Attachment A – MarFC Project Overview Presentation prepared by Joe Pratt, Sandia National Laboratory

Attachment B – Primary Training Presentation prepared by Jennifer Hamilton (CaFCP) and Monte Elmore (PNNL).

Attachment C – "Hydrogen Fuel Cell Demonstration Project at Port of Honolulu." Summary sheet prepared by SNL staff for handouts at training.

Attachment D – "Safety Features Integrated into Design and Use of System." Summary sheet prepared by SNL staff for handouts at training.

Attachment E – A selection of attendee Questions and Comments discussed at some of the training sessions.

Attachment F – Attendee lists for each of the training sessions in Honolulu and Kahului.

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Attachment A

MarFC Project Overview Presentation

prepared by Joe Pratt, Sandia National Laboratory

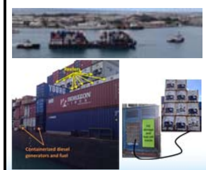
Maritime Fuel Cell Project Overview for Hydrogen Safety Training Attendees

Young Brothers Honolulu
April 9-10-11, 2015
Kahului Fire Station
April 15-16-17, 2015

Agenda

- What we are doing and why
- Overview of use and handling considerations

We are building and demonstrating a containerized hydrogen fuel cell generator for reefer power on land and sea.



Project Concept

Fuel cell unit replaces diesel generators, reducing fuel cost and emissions.

Project Scope

Design, build, and deploy a containerized fuel cell system to supply portable power for refrigerated containers ("reefers").

- 100 kW (net) fuel cell and H_2 storage inside a 20-foot container.
- 6-month deployment on land and over the ocean. (Honolulu-Kahului)
- Strategic set of project partners, encompassing both the H_2-fuel cell and maritime communities.

Project Timeline and Progress

1. Establish team and define prototype (Sept. – Dec. 2013)
2. Design prototype, H_2 supply logistics (Jan – Dec. 2014)
3. Build generator and site prep (Dec. 2014 – June 2015) ← We are here
4. Deploy on dock and on barge (June – Nov. 2015)

Generator should arrive at YB late May/early June

Many people have contributed to getting us this far. Thank you in advance for adding your efforts during the upcoming deployment.

DOE: *Project Sponsor and Local H_2 Infrastructure*

Sandia: *Technology Support and Project Management*

DOT/MARAD: *Project Sponsor*

Young Bros. and Foss Maritime: *Deployment Partners*

Hydrogenics: *Complete design, build, and integration*

HNEI: *Local H_2 Facilitator*

American Bureau of Shipping: *Maritime Product Certification*

Hydrogen Safety Panel: *Project and prototype safety review*

US Coast Guard and USCG Sector Honolulu: *Maritime codes and standards*

HCATT: *Hydrogen provider*

Logos used with permission

Why are we doing this?

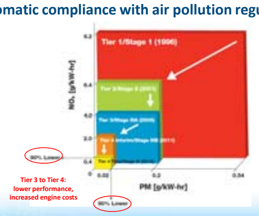
Technology Reasons
- Test and refine technology in the marine environment

Regulatory Reasons
- Enable future hydrogen fuel cell maritime uses

Environmental Reasons
- Reduce pollutant and greenhouse gas emissions

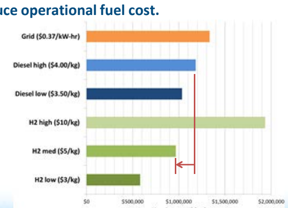
Economic Reasons
- Potential to be an affordable, competitive alternative to diesel
- Develop new market for fuel cells

This generator has zero emissions, ensuring automatic compliance with air pollution regulations.



Graphic by *Cummins Emissions Solutions*

The technology has the long-term potential to reduce operational fuel cost.



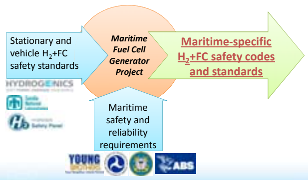
This project is a stepping stone and helps to refine the technology.

We are here

< 200 kW / > 1 MW

Dockside	Barge/Vessel
Small Demo • Verify FC-to-reefer concept • Solves local H_2 issues (availability, price, permitting) • FCs in maritime environment	**Small Commercial** • Containerized FC and H_2 • Critical service • USCG H_2 protocol development • Real-world cost savings
Large Demo • Ship interface. • Many reefers (via ship electrical). • Large scale containerized FC.	**Large Demo** • Large scale FC and H_2 on floating platform. • On-barge H_2 refueling.
Large Commercial • Critical service • Fuel cost savings • Infrastructure savings • Wider applicability	**Large Commercial** • Critical service • Fuel cost savings • Infrastructure savings • Wider applicability • Highest utilization

We are assisting the development of maritime codes and standards for hydrogen and fuel cells



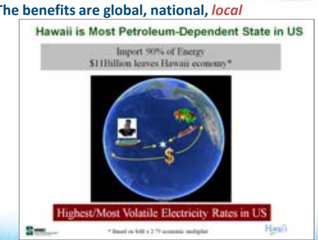
The design is based on stationary and vehicle safety standards and modified to meet maritime requirements; the result is helping inform future codes and standards.

Support from the Coast Guard

"The CFR currently has no specific regulations regarding fuel cell installations. We hope that this trial installation and the associated design standards can help the USCG, vessel classification societies such as ABS, and other organizations such as IMO, develop standards and policies specifically applicable to fuel cell installations. Thank you for your efforts in helping to bring a renewable energy source to the maritime sector."

-R. W. Martin
Acting Chief, Systems Engineering Division
U.S. Coast Guard
Sept. 10, 2014

The benefits are global, national, *local*

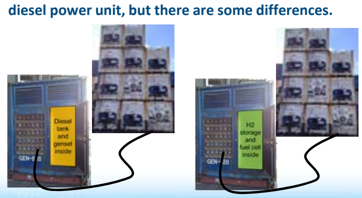


Slide courtesy of Hawaii Natural Energy Institute

Agenda

- What we are doing and why
- **Overview of use and handling considerations**

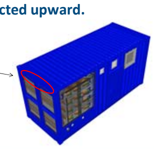
The generator will look nearly the same and power the refrigerated containers in the same way as the diesel power unit, but there are some differences.



For one, it will be quieter and have zero emissions

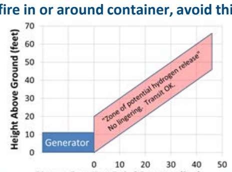
If there is a fire in or around the unit, relief valves prevent the hydrogen tanks from exceeding their pressure limits. The vents are at the top of the end and are directed upward.

Location of relief vents



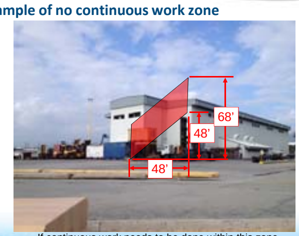
Releases are NOT part of normal operation. Only occur if (1) fire or (2) defect in a relief valve.
Probability of failure due to defect is ~0.0005 (same as once in 5+ years).

As an extra precaution we are recommending no continuous work in the area shown. Transit is OK. If there's a fire in or around container, avoid this area.



Releases only occur if fire or by defect in a relief valve.
Probability is ~0.0005 (same as once in 5+ years).

Example of no continuous work zone

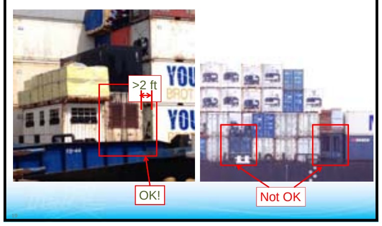


If continuous work needs to be done within this zone, recommend re-orienting the generator.

Fuel cells need to breathe. The vents are located on one side of the container and need 2-foot clearance.

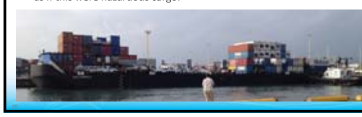
Vents are marked and highlighted in yellow

Example of locating the generator with room on the vent side.



Other considerations – Stowing on the Barge

- Kahului barge, mid-ship stow.
- 2-foot clearance on vented side.
- Hydrogen relief vent end pointed outward/away.
- Hazmat segregation: Although not required by regulation, and not necessary because of designed safety features, out of an abundance of caution for this demonstration, YB plans to follow segregation rules as if this were hazardous cargo.



Forking is OK from one side, but toppick preferred whenever possible, as extra precaution against damage.

The operator interface is all external. It has on/off controls, status indicators, and an emergency stop button.

The generator has numerous internal, automatic safeguards, described in detail later.

Exceptions & YB Internal Notification Procedure

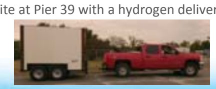
- Signs of an exception:
  - Audible alarm is sounding
    - Generator has detected a potentially-hazardous hydrogen leak and has shut down the generator and closed the hydrogen supply tanks
  - Very loud hissing noise
    - Possible component failure and the system may be leaking hydrogen.
  - Red status light is lit (without audible alarm)
    - Generator has detected a non-hazardous fault and stopped
  - Unit does not seem to be producing power
    - Check generator status lights
- For any exceptions or concerns, make notification via:
  - Your immediate supervisor and/or
  - Port Engineer, Barges (Gavin)

The generator monitors itself; the operator does not need to figure out what is happening inside to know if it s work ng or not

Refueling with hydrogen: YB has two options

1. Off-site at Hickam AFB for direct fill (initial plan)

2. On-site at Pier 39 with a hydrogen delivery service



YB Training Plans

1. This training: Management & supervisory personnel. A video of this training will be available for anyone who missed it.
2. In May at Hon Ops monthly safety meeting, managers will cover an abbreviated version of this training with designated Shoreside and Marine Operations and Maintenance employees.
3. After the generator arrives, around end of May to early June, additional operational training directly from the manufacturer will be provided to selected employees who need additional information for their job functions (*e.g.*, Maintenance, Service group, Utilities, Managers/Superintendents).

- Any Machine Operator (MO) or other employee who has not received this training should not be allowed to move or operate the generator. The YB Safety team will be tracking training records for everyone and Managers/Superintendents should plan accordingly.

Thank you

For your participation today

and

For your help with a safe and successful deployment

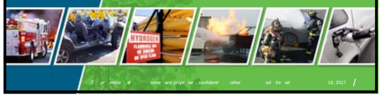
Attachment B

Primary Training Presentation

National **Hydrogen and Fuel Cells Emergency Response TRAINING for Sandia/Young Bros. Maritime Demonstration**

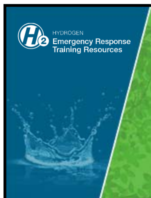
prepared by Jennifer Hamilton (CaFCP)

and Monte Elmore (PNNL)



HYDROGEN Emergency Response Training Resources

National
Hydrogen and Fuel Cells
Emergency Response
TRAINING
for Sandia/Young Bros.
Maritime Demonstration



Fuel Cell Electric Vehicles (FCEV)

- Run on hydrogen
- Use a fuel cell and electric motor, no engine
- Quiet, mostly air compressor and valves
- Emit zero pollutants

California ZEV Action Plan

- By 2015: California major metropolitan areas "ZEV-ready" with infrastructure and streamlined permitting
- By 2020: California ZEV infrastructure can support up to 1 million vehicles
  - Including widespread use of ZEVs for freight and public transit
- By 2025: Over 1.5 million ZEVs in California

cafcp.org/toolkits/cities to download the ZEV Action Plan

Stations must come first

- 68 stations provide coverage to enable market launch
  - Supports customer convenient fueling in early markets
  - Enables travel throughout early market regions and state
- 100 stations to support market growth

Supporting the Mission of H2USA

- The mission of H2USA is to promote the commercial introduction and widespread adoption of FCEVs across America through creation of a public-private collaboration to overcome the hurdle of establishing hydrogen infrastructure.
- Having properly trained first responders will address a key barrier, ensure a safe transition to fuel cell vehicles and H2 infrastructure, and pave the way for broader public acceptance.

H2USA's public-private partnership

Key Early Market Challenges Addressed by H2USA

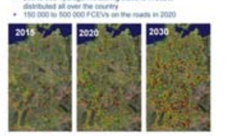
- **Station Cost Reduction**
  - Fueling resources & delivery
  - State and local regulations
- **Station Locations**
  - Identify and prioritize markets
  - Regulatory barriers (zoning)
  - Station rollout timing
- **Investment and Finance**
  - Private sector financing
  - Government support
- **Market Support and Acceleration**
  - Product launch and timeline
  - Codes and standards (non-vehicle related)
  - Public education

Photo Credits Top: NREL, Middle NREL, Bottom: Hexagon Lincoln

Public-Private Partnership

H2 mobility in Germany

- Initiative gathering the German government and industrial companies
- 200 to 500 hydrogen refuelling stations in 2020, distributed all over the country
- 150 000 to 500 000 FCEVs on the roads in 2020



1/16/2017 / 8

2-2 Joint Announcement by 13 Japanese Companies

(2011/1/13)

Automakers (3 private companies):
Toyota Motor Corporation, Nissan Motor Co., Ltd., Honda Motor Co., Ltd.

Hydrogen fuel suppliers (10 private companies):
JX Nippon Oil & Energy Corporation, Idemitsu Kosan Co., Ltd., Iwatani Corporation, Osaka Gas Co., Ltd., Cosmo Oil Co., Ltd., Saibu Gas Co., Ltd., Showa Shell Sekiyu K.K., Taiyo Nippon Sanso Corporation, Tokyo Gas Co., Ltd., Toho Gas Co., Ltd.

1. Automakers are aiming to launch FCVs in the Japanese market—mainly in the country's four major metropolitan areas—in 2015.
2. Hydrogen fuel suppliers are aiming to construct approximately 100 hydrogen stations by 2015.
3. Automakers and Hydrogen fuel suppliers will work together to expand the introduction of FCVs and develop the hydrogen supply network throughout Japan.

In four metropolitan areas local government, local METI and private companies established joint committee to disseminate the strategy for the initial demand creation in the region.

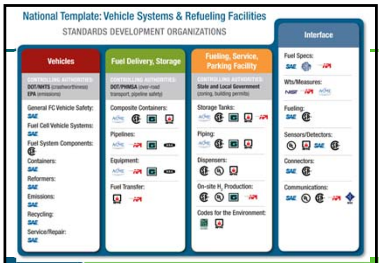
■ METI, Chubu Bureau of METI, Osaka Prefecture and Fukuoka Prefecture simultaneously press released.

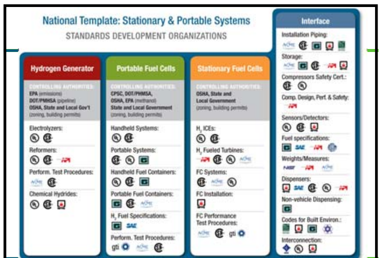
Toyota Mirai FCV

MIRAI

https://www.youtube.com/watch?feature=player_embedded&v=GUjYIaUGmqU

More than cars…





Project Concept: Containerized H_2 Fuel Cell Generator

Project Scope

- Design, build, and deploy a 100 kW fuel cell system to replace diesel generator
- 6-month deployment (2015) on land and over the ocean
- Safety, Operational , and Regulatory procedures in development
- Affordability and Accessibility of hydrogen fuel

Project Overview

- The objective is to design, build, and deploy a 100kW fuel cell generator unit that would replace diesel generator units used for powering refrigerated shipping containers.
- The unit would first be deployed on land in a shipping port in Hawaii.
- After an evaluation period on land the unit would then be deployed on board unmanned barges making trips in between the islands of Hawaii.
- The deployment period (both on land and on sea) is scheduled to last an initial period totaling 6 months.
- Up to a maximum of 10 refrigerated containers could be powered at one time and enough Hydrogen to support a round trip between the islands would be stored on board.

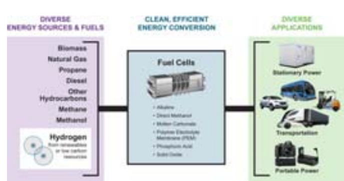
SECTION 1:

Introduction and Background

This section introduces the user to:

- An overview of the role of fuel cells and their benefits
- A picture of today's hydrogen production and delivery, current markets for fuel cells
- A diverse set of fuel cell transportation applications

Fuel Cells Overview



Fuel Cells

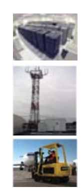
Where are We Today?

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts

More than 35,000 fuel cells shipped in 2013
(~a consistent 30% annual growth since 2010)

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts



Fuel Cells
Where are We Today?

Production & Delivery of Hydrogen

In the U.S., there are currently:
- ~9 million metric tons of H_2 produced annually
- > 1,500 miles of H_2 pipelines

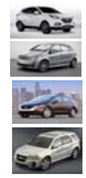
Source: US Department of Energy 2009/2010

Fuel Cells
Where are We Today?

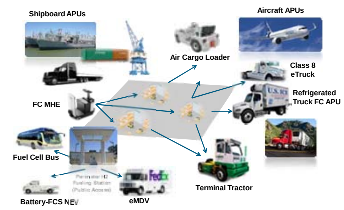
Fuel Cells for Transportation

The US DOE completed the world's largest FCEV and hydrogen demonstration to date for all purposes (with 50/50 DOE/Industry cost share)
- More than 180 fuel cell vehicles
- 25 fueling stations ~3.6 million miles travelled (~500,000 trips)

Several automakers have announced commercial FCEVs in the 2015-2017 timeframe
- ~100 stations in CA by 2021



Diverse Fuel Cell Transportation Applications



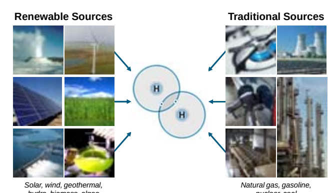
SECTION 2:
Hydrogen and Fuel Cell Basics

This section covers:
- Basic properties and behaviors of hydrogen
- How hydrogen compares to other fuels
- How a hydrogen fuel cell works
- Potential hazards with hydrogen that may differ from those of other fuels
- The controls commonly used to assure the safe use of hydrogen

Why Hydrogen?

- Excellent energy carrier
- Nonpolluting
- Economically competitive
- As safe as gasoline
- Used safely for over 50 years
- Produced from a variety of sources

Where Do We Get Hydrogen?



Hydrogen Uses

The use of hydrogen is not new; private industry has used it safely for many decades. Nine million tons of hydrogen are safely produced and used in the United States every year. 56 billion kg/yr are produced globally. For example, H_2 is used for:

- Petroleum refining
- Glass purification
- Aerospace applications
- Fertilizers
- Annealing and heat treating metals
- Pharmaceutical products

The Air Products and Chemicals hydrogen production facilities in Port Arthur, Texas, is funded by the Energy Department through the 2009 Recovery Act. | Photo credit Air Products and Chemicals hydrogen production facilities.

- Petrochemical manufacturing
- Semiconductor industry
- Hydrogenation of unsaturated fatty acids in vegetable oil
- Welding
- Coolant in power generators

Hydrogen Distribution

- DOT regulated transportation…
- Cryogenic liquid transport
  - -423°F (-253°C)
  - Low pressure (<100 psi)
- Pressurized gas trailers
  - ~2,000-6,500 psi
- Truck, rail, barge and pipeline

Photo: Praxair, Inc.

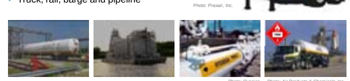
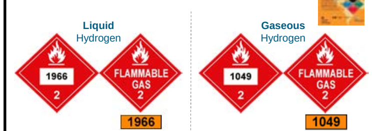


Photo: Oxenics Photo: Air Products & Chemicals, Inc.

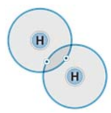
Transporting Hydrogen Today

DOT placards for commercial transport of hydrogen



Hydrogen Properties and Behavior

- A gas at ambient conditions
- Hydrogen is a cryogen: exists as a liquid at -423°F (-253°C).
  - Compressing the gas does not liquefy it
  - No liquid phase in a compressed gaseous hydrogen storage tanks
- LH2 storage at relatively low pressure (50 psi)
- Double walled, vacuum insulated tanks with burst disks, vents, and PRDs
- Volumetric ratio of liquid to gas is 1:848
  - Compare water to steam (1:1700)
- Energy content of 1kg of H_2 is approximately equal to 1 gal of gasoline (in BTUs)



Molecular Hydrogen

Hydrogen Properties: A Comparison

	Hydrogen	Natural Gas	Gasoline
Color	No	No	Yes
Toxicity	None	Some	High
Odor	Odorless	Mercaptan	Yes
Buoyancy Relative to Air	14X Lighter	2X Lighter	3.75X Heavier
Energy by Weight	2.8X > Gasoline	~1.2X > Gasoline	43 MJ/kg
Energy by Volume	4X < Gasoline	1.5X < Gasoline	120 MJ/Gallon

Source: California Fuel Cell Partnership

Comparison of Flammability

	Hydrogen	Natural Gas	Gasoline
Flammability in air (LFL – UFL)	4.1% - 74%	5.3% - 15%	1.4% - 7.6%
Most easily ignited mixture in air	29%	9%	2%
Flame temperature (°F)	4010	3562	3591

Gas properties & characteristics

- Displaces O2 (Asphyxiant)
- Burns with a pale blue flame
  - near invisible in daylight (can see what it burns)
  - much less radiant heat of gasoline fire

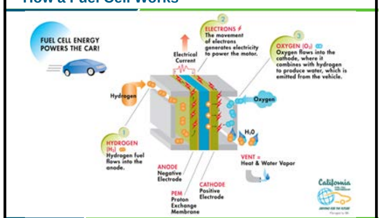
Fuel Cell Basics

- The type of electrolyte determines the kind of fuel cell
  - The polymer electrolyte membrane fuel cell is the most promising for light-duty transportation
  - Other fuel-cell types, such as solid oxide, molten carbonate, and phosphoric acid fuel cells, use different electrolytes
- To increase the amount of electricity generated, individual fuel cells are combined into a fuel-cell "stack," which may consist of hundreds of individual fuel cells

Photo: National Renewable Energy Laboratory

Photo: California Hydrogen Business Council

How a Fuel Cell Works



H12

Fuel Cell Power Module (FCPM) Build

HYDROGENICS

All four HD30's built

SECTION 2b:

Hydrogen fuel storage

This section covers:

- Compressed hydrogen storage systems
- Types of cylinders
- Cylinder qualification testing and safety

Onboard Hydrogen Storage

- Hydrogen can be stored as a gas or liquid
- To date, light duty vehicles use gaseous hydrogen
- Gaseous hydrogen: 35 or 70 MPa (approximately 5,000 or 10,000 psi, respectively)
- Passenger vehicles typically store up to 6 kg of hydrogen gas
- Buses with multiple tanks can store as much as 40 kg to 50 kg of hydrogen gas
- To date, buses carry gaseous hydrogen

Toyota Mirai fuel cell sedan power train, seats, and hydrogen tanks
Source: http://newsroom.toyota.co.jp/en/detail/4198334

Compressed Hydrogen Storage Systems

- Carbon fiber wrapped, metal or polymer lined tanks
- Equipped with temperature activated pressure relief devices (PRD/TRD)
- Stronger than conventional gasoline tanks
  - Absorb 5X crash energy of steel

Wall thickness comparison:
35 MPa vs. 70 MPa cylinders

(Photo courtesy of Powertech)

Compressed Hydrogen Tank Testing

- Bonfire
- Drop
- Gun fire
- Pressure cycling
- Overpressure
- Temperature
- Impact
- Permeation
- "Tank life" – at least 15 years
- Rated for 2.25x service pressure

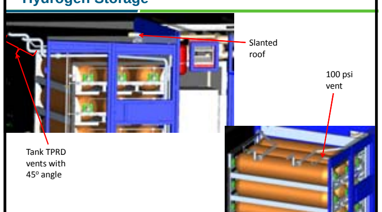
Compressed Hydrogen Tank Testing

- In accordance with latest proposed hydrogen vehicle tank standards (SAE J2579, CSA HGV2)
- Tests conducted as part of the design qualification testing for new tanks
- Vent only, no rupture

Hydrogen Storage Cylinder Testing and Certification

- Cylinders are ANSI/AGA NGV-2 certified. "American National Standard for Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers"
- Cylinder qualification testing:
  - Strength and Life Cycle: burst, ambient cycling, leak before break, accelerated stress, rupture, hydrogen cycling, boss torque
  - Environmental: environmental fluid exposure, extreme temperature cycling, bonfire
  - Damage Tolerance: penetration (gunfire), flaw tolerance, drop
- For each batch produced:
  - the liner of one tank is subjected to burst testing and destroyed
  - one complete tank is subjected to life cycle testing and undergoes metallurgical analysis
- For an order of 15 tanks, 16.5 tanks will be produced

Hydrogen Storage



SECTION 3:

Containerized Hydrogen Fuel Cell Generator

This section covers:

- Key technical specifications
- System overview
- System controller functionality
- System safety
- System components
- Routine operation
- Emergency stop

Key Technical Specifications

- On board Hydrogen Storage: 74.7 kg @ 5000 PSI
- Hydrogen storage compartment open to atmosphere with slanted roof and integrated hydrogen detection.
- Generator room cut off from Hydrogen supply when system not in operation, equipped with two hydrogen detectors and active ventilation.
- Fuel Cell System: 4 x HD30, 120 kW gross output, 240-480 VDC, 0-500 amps
- Ultra-Capacitor System: 3.9 Farads, 0-480 VDC, 0-170 amps
- VRLA 24V Battery System: 31 Ah, 24V, maintenance free
- Inverter: 120 kW gross output, dual input channel, 240V 3-Phase Wye
- AC Output Power: 10 Plugs at 50 Amps maximum per plug
- 3/16" Steel checker-plate floor

System Overview

1. 120kW Fuel Cell Rack
2. Electrical Cabinet
3. 120kW Inverter
4. User Interface
5. Reefer Plug Assembly
6. Intake Air filter
7. Fuel Cell Exhaust
8. Generator Room Ventilation Exhaust
9. Fuel Cell Chemical Filter
10. H2 and Smoke Detector Location (1)
11. H2 Detector Location (2)
12. H2 Fill Port
13. Coolant Reservoir
14. Coolant Pump
15. TPRD Relief (1)
16. TPRD Relief (2)
17. H2 Detector Location (3)

2: Electrical Cabinet Contains: OSC, VRLA Batteries, Ultra-Caps, Contactors

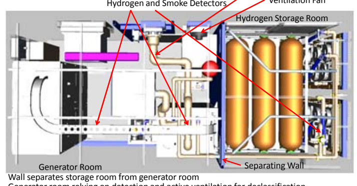
Overall Governing Standards Skeleton

	Hyd ogen Sto age Sy em	Hyd ogen Piping	Non Hyd ogen Piping (Coolan	Ele ca and Wi ng	Fue Cell Ra k	Inve e	Lead Acid Star up Battery	Ul a Capa to Sto age Sy em
Applicable Standards	NGV-2 "American National Standard for Natural Gas Vehicle Containers"	ASME B31.12 "Hydrogen Piping and Pipelines"	ASME B31.3 "Process Piping	NFPA 70 UL 508 UL 1604 UL 913	FC1 and UL	UL 1741 ANSI 535 NFPA 704 IEEE 519-1992TM	UL CE IEC 61056-1, JIS C 8702-1, GB/T 19639.1 EC	IEC 60068-2-6 IEC 60068-2-27 IP54
Reasoning /Inspection Body / Supplier	NGV 2 and HGV 2 both acceptable – currently no HGV 2 cylinders (no demand from manufacturer)	TSSA: Technical Standards and Safety Association	TSSA: Technical Standards and Safety Association	QPS	Design standard for all Hydrogenics FCPM designs	Applicable standards governing inverters used with distributed sources	All applicable Valve regulated lead acid battery standards	Shock and vibration specs and IP rating: safety through analysis

Overall System Controller (OSC) Functionality

- Monitor status of the safety system including all hydrogen and smoke detectors, and ESTOP line
- Drive tank solenoid valves and read the status of all tank pressure transmitters
- Provide controls and monitor the status of all radiators, ventilation fans, and coolant pumps
- Drive indicators on the outside of the container
- Monitor the status of the ultra-capacitor series voltages
- Provide communications between the FCPR and the inverter

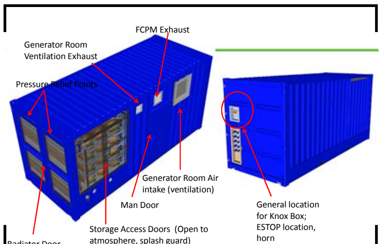
Hazardous / Non Hazardous Zones



- Wall separates storage room from generator room
- Generator room relying on detection and active ventilation for declassification
- Storage room relying on opening to atmosphere at highest point and buoyancy of hydrogen

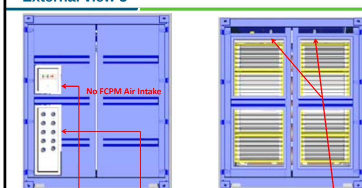
Unit Safety System Overview

- Hydrogen gas detectors
- Smoke detectors
- ESTOP (hard wired to electrically activated tank solenoid valves)
- TPRDs (2 per tank) and PRD (on 100 psi line)
- Regulators (2 in series)
- Hydrogen control valves (Tank valve, 3 low pressure solenoids, and Hydrogen supply valve all must be activated for fuel to reach any fuel cell stack → 5 valves)
- Pressure switch shuts down all solenoids before any over-pressure situation should be reached
- Emergency vent stacks
- Flow restricting orifice to protect against pipe breakages
- Redundant safety checks upon startup
- Passive and active ventilation



External view 3

Storage room vent at highest point of slanted roof (open to atmosphere)



Front: User interface panel; Reefer plugs (10)

Back: Hydrogen storage, louvered doors, hydrogen vents

Hydrogen Supply Room: Design for Passive Ventilation

- Common sense approach relying on natural convection and opening at highest point of container
- Slant: 60mm rise on 2m of length
- Does not allow hydrogen to fill cavities between stacked containers as an opening directly in the roof would
- Vents at 45 degrees upward, flush with door face

Hydrogen Supply

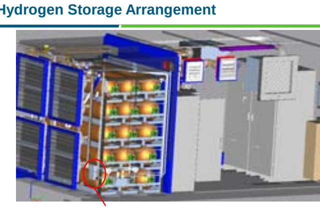
1. Flow restricting orifice to protect against pipe breakage
2. One electronic solenoid per tank (15)
3. High pressure transmitters on high pressure line (2)
4. Regulators connected in series (2)
5. Pressure Relief Valve
6. 100 PSI supply solenoid cutoff
7. High pressure gauge
8. Low pressure gauge

Hydrogen Supply Room Radiators

- Brushless DC Motors
- Mounted below the vent for the container
- 8 radiators (30kW rejection per radiator)
- Fully sealed controller design

- Utilizes same fan as the ventilation fan in the FCPM (200 to >1000 CFM per fan depending on pressure)
- Total of 16 fans
- Dielectric grease applied to all connectors

Hydrogen Storage Arrangement



Hydrogen and smoke detection

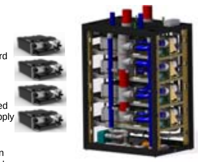
- Hydrogen sensors located in the hydrogen storage room (1) and in the generator room (2)
- Smoke detector located in generator room (1)
- Sensors are powered from the 24 v battery when all other components are off
  - Other than in ESTOP or SYSTEM OFF mode, sensors are powered

Generator Room – Hydrogen Piping and PRD

- FCPM rack equipped with two redundant solenoid valves for hydrogen supply: UL listed, CSA certified, CE compliant. Additional valve for 100 PSI shutoff in storage. (3 in series total)
- Each FCPM within rack equipped with own OVP switch, supply solenoid valve and pressure transmitter
- Each FCPM equipped with air blower operating at 70 CFM at full power (total additional flow in generator room of 280 CFM at full power)

120 kW Gross Power FC Rack

- Four (4) HyPM™ HD 30 Fuel Cell Power Modules19" plug-in form factor
- 19" Rack with cooling, reactant and ventilation manifolds
- Rated 120 kW total raw DC Power Output
- Designed to comply with UL standard FC1
- Dual redundant UL rack supply solenoids
- Each FCPM equipped with integrated over-pressure switch, dedicated supply solenoid, and dedicated pressure transmitter.
- All FCPM's are fully leak checked on build and have built in self leak check capabilities



Inverter

- 120kW, 240Vac, 3P-Y output with built in circuit breaker
- Air cooled power electronics for -10 C to 40 C operation
- Designed to comply with UL 1741: "Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources": These requirements cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in stand-alone (not grid-connected) systems
- Includes an ESTOP

Ultra capacitors

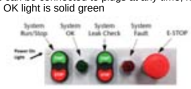
- 170 Amp per module (340 Amp) max current
- Sealed ruggedized IP54 enclosure
- Vibration and shock to IEC60068-2 and IEC60068-27
- Manufacturer has conducted extensive safety testing on these cells including: penetration, crush, impact, over-voltage, short circuit, flammability and heat testing with a safe (no fire, flame or explosion) failure mechanism exhibited in each case.
- Each of the series elements in the system will have their module voltages monitored so as not to exceed 150V and the system will be fused at 170 Amps

24 volt battery and power supply

- 24 volt startup batteries:
  - Two by 31 Amp-Hour 12V batteries in series
  - Valve Regulated Lead Acid (VRLA) Technology
  - Sealed, maintenance free
  - Due to use of VRLA technology there is no Hydrogen venting.
  - UL 508 Listed and CE certified and compliant
- 24 volt power supplies:
  - Provide 24V power while Fuel Cell is in operation
  - 10kW 24V power supply for powering radiator fans, water pump, ventilation fan, and maintaining charge of 24V startup battery.
  - Internal over voltage protection (125% of nominal input voltage)
  - Internal over current protection (110-120% of full load)
  - Over temperature protection
  - Safety: UL1950, CSA 22.2 No 590 and TUV to EN60950, CE Mark

Routine operation- start up = hold START 1 sec

- Automated process
- Hydrogen and smoke detectors are activated
  - During leak check all gas supply valves are shutoff and all high voltage contactors are de-energized
- Ventilation system activated
- Leak and safety checks conducted by the system*
- Total system startup time approximately 4-5 minutes
- Reefers can be connected to plugs at any time, no power until System OK light is solid green



*minimum action: system trouble must be cleared by user; maximum action: total system shut down

Routine operation – shut down = press STOP

- Inverter output disabled
- Tank solenoid valves shut (isolating fuel in the tanks)
- FC system goes into shutdown mode
  - 100 psi lines purged- vent to atmosphere
- Entire shutdown takes approximately 1 minute*

* Ultra capacitors are isolated upon initial shut down and ultimately discharge over time

Automated leak check (initiated by user)

- Push "START" on System Leak Check button
  - enables the 24V start-up battery
- "System Ok" light will flash quickly indicating a hydrogen leak detection check is being conducted. (Takes approximately 1 minute)
- If hydrogen leak check **fails** → Red "System fault" light will go on and the audible alarm will sound
  - the alarm will stay on until the "E-STOP" is pushed or the level of hydrogen drops below a non-hazardous concentration
  - the source of the hydrogen leak needs to be found by a trained responder
- If hydrogen leak check **passes** → Green "System Ok" light will transition to a very slow flash
  - the status of the hydrogen sensors will be continuously monitored during this mode
- To exit this mode push the "Stop" on the System leak check button

Note: Leaving the System in leak check mode continuously for extended periods of time (2-3 days) without running the system will deplete the 24V start-up battery and the battery will need to be topped up by an external power supply.

Emergency Stop

- An operator can at any point in time push the E-Stop button in the user interface to de-energize the system
- Additional ESTOP locations:
  - inside the generator room(2)
    - on the inverter
    - additional one inside the generator room

Green Light Indicator Summary

During Leak Check pushing the stop button turns off the system within a couple seconds.

During run mode pushing the stop button sends the unit into shutdown mode which during which time the hydrogen lines in the generator room are depressurized and the blowers are spooled up to eliminate excess water from the fuel cell. During shutdown the light will change from solid green to a slow flash (every 4 seconds).

System Run – Green Light Control			Hydrogen Detect Mode – Green Light Control	
Start-up	Run Mode	Shutdown	Leak Check in Progress	Leak Check Success
Fast Flash (1 second on/off)	Solid	Slow Flash (4 second on/off)	Fast Flash (1 second on/off)	Slow Flash (4 second on/off)

Indicators and alarm overview

- An audible alarm → a trained responder should be contacted
  - investigate if a hydrogen leak has occurred and determine source of the leak
- A solid red light (without an audible alarm) → a non-hazardous fault has occurred
  - The stop button can be pressed by the operator and Hydrogenics technical support should be contacted for trouble shooting assistance
- A slowly blinking green light in Hydrogen Leak Check mode → there is no Hydrogen leak
- A solid Green light in run mode → the system is running

SECTION 4:

Stationary Facilities

This section describes and discusses:

- Types of stationary facilities
- Options for bulk transport and storage of hydrogen
- Stationary hydrogen fuel cell applications
- Components and configurations of a hydrogen fueling station
- Safety features of a stationary facility

Types of Stationary Facilities

Stationary facilities include:

- Stationary fuel cells
- Bulk hydrogen storage
- Hydrogen fueling stations


Photo: Air Products and Chemicals, Inc.

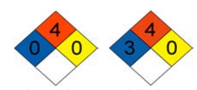

Photo: Plug Power, Inc.


Photo: California Fuel Cell Partnership

Identifying Stationary Facilities

NFPA 704 Hazard Placards

- Red = Flammability
- Blue = Health
- Yellow = Reactivity
- White = Special Precautions



Gaseous Hydrogen   Liquid Hydrogen

Components for Fueling a Hydrogen Vehicle

- The dispensing nozzle "locks on" to the vehicle before any hydrogen will flow
- Hydrogen dispensers are equipped with safety devices:
  - Breakaway hoses
  - Leak detection
  - Grounding platform


Photo: California Fuel Cell Partnership

Hydrogen Fueling

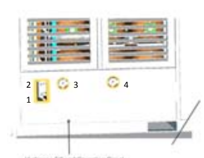
- Closed-loop design, no leaks or vapors
- Experienced suppliers and providers: Linde, Shell Hydrogen, Air Products, Air Liquide, Hydrogen Frontiers, ProtonOnsite, HyGen Industries and others


35 MPa Nozzle


70 MPa Nozzle

H55

Hydrogen Refueling Access Panel



1. Refueling Port
2. Low Pressure (100 PSI) defueling Port
3. High Pressure Gauge
4. Low Pressure Gauge

General Station Safety Systems

- Pressure relief systems
  - Burst disks
  - Pressure relief valves/devices (PRV/PRD)
  - Safety vents
- Fire and leak detection systems
  - Telemetric monitoring
  - Hydrogen gas detectors
  - UV/IR cameras
  - Fueling line leak check on nozzle connect

General Station Safety Systems

- Design elements
  - Engineering safety margins and analysis (HAZOP, etc.)
  - Hydrogen compatible materials
  - Siting to established regulations
  - Cross-hatched areas for user attention
- Other systems
  - Emergency stops
  - Dispenser hose break-away devices
  - Impact sensors at dispenser
  - Controlled access
  - Excess flow control (fueling)
  - Pre-coolers (-40°F)

Typical Station Configurations

- Hydrogen can be delivered or made on site
- Liquid delivered → gaseous H_2
- Gaseous delivered or piped → booster compressed gaseous H_2
- Natural gas → gaseous H_2
- Water + electricity → gaseous H_2

Hydrogen Fueling Stations

Hickam AFB station

http://www.pacaf.af.mil/shared/media/photodb/photos/090513-F-5608V-019.JPG

Hydrogen Fueling Stations
Gaseous Hydrogen Delivery

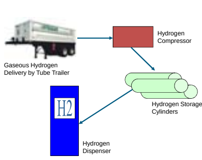
Gaseous hydrogen can be delivered to the fueling station by tube trailer or mobile refueler

Photo: National Renewable Energy Laboratory   Photo: U.S. Department of Energy

Hydrogen Fueling Stations
Gaseous Hydrogen Storage

Gaseous hydrogen is:

- Delivered to fueling station by tube trailer
- Compressed and stored onsite in cylinders
- Piped to dispenser for fueling vehicles

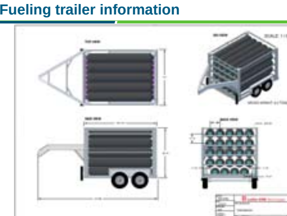


Graphic: Pacific Northwest National Laboratory

Fueling trailer information

- 24 cylinders
- working pressure of 450bar/6,527psig
- 220 kg hydrogen capacity at 450 bar
- Est. gross weight 12,500 lb
- Towable by 1-ton pickup
- Automotive nozzle to match automotive receptacle on prototype
- Fill prototype in one hour or less
- Trained technician, familiar with hydrogen stations, to perform each fill

Fueling trailer information



Fueling trailer information

SECTION 5:

Managing Hydrogen-related Emergencies

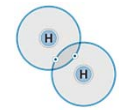
In this section, we want to:

- Discuss potential hazards associated with hydrogen vehicles and stationary facilities
- Discuss emergency response actions for both vehicle and facility incidents within the context of the National Fire Academy (NFA) Command Sequence
- Identify sources for additional emergency response information useful in dealing with a hydrogen incident

Considerations for Managing Hydrogen-related Emergencies

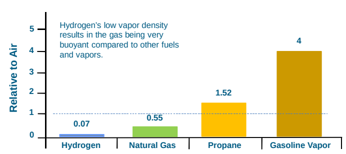
Buoyancy of hydrogen gas:

- It's 14 times lighter than air
- When released outside, it rises at ~45 mph
- It's a small molecule and very difficult to confine
- When released inside, it quickly finds its way through most materials
- Due to an inverse Joule-Thomson effect, hydrogen does not cool the surrounding environment (won't cause ice on the valve)

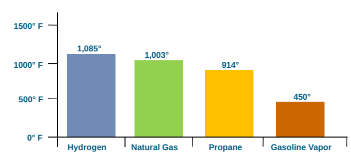


Molecular Hydrogen

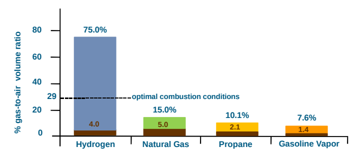
Relative Vapor Density



Auto-ignition Temperature



Flammability Range



Considerations for Managing Hydrogen-related Emergencies

Radiant heat:

- The hydrogen flame is ~ 4010 °F, but no radiant heat is produced. Responders may not feel heat until almost in the flame
- Gasoline releases carbon when it burns, so radiant heat can be felt from a great distance
- Due to CO_2 released when burning, E85 produces twice the radiant heat as the same volume of gasoline

Compressed Hydrogen Tank Testing

High Strain Rate Impact Test

Gunfire test of 35 MPa hydrogen tank:

- Objective: penetrate tank while pressurized
- Tank filled with hydrogen to 5,000 psi
- 30 caliber armor piercing bullet, 45° angle
- Simulate a high-strain rate penetration event due to collision

Compressed Hydrogen Tank Testing

Bonfire Test

Bonfire test of 70 MPa hydrogen tank:

- Objective to simulate vehicle fire; entire tank engulfed
- Tank filled with hydrogen to 10,000 psi
- Subjected to a propane burner fire, 1.65m long
- PRD activated and hydrogen vented to atmosphere without incident

National Fire Academy (NFA) Command Sequence

1. Size Up (Think) — SIZE-UP
2. Identify Strategy/Tactics — PLAN
3. Assign Tasks — ACT
4. Review Results of Actions/Critique — EVALUATE


Photo: Volpentest HAMMER Federal Training Center

Follow SOPs for response, paying particular attention to unique systems and characteristics for hydrogen-powered fuel cells

Hydrogen Incident

SIZE-UP

Considerations during incident size up:

- Hydrogen fuel tank
  - Is there fire?
  - If so, is it impinging the hydrogen tanks?
  - Is the tank currently venting?
  - Has the tank already vented?
- Hydrogen fuel
  - If the hydrogen is venting, is it burning?
  - If the hydrogen is not burning, are there potential ignition sources?
  - Can the hydrogen be dispersed to levels below the LFL?

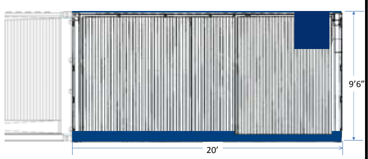
Hydrogen Power Unit

SIZE-UP

High-Voltage System, Potential Ignition and Shock Hazard:

- Are any of the high-voltage components exposed? Avoid these until fully deactivated
  Note: Power remains in system for 5 minutes after deactivation
- Is the ultra-capacitor on fire?

Unit identification (formal and informal)



Unit identification (formal and informal)

On the man door

Stationary Facilities

SIZE-UP

Stationary hydrogen facilities will have hazards similar to facilities with other compressed and/or cryogenic gas processing or storage systems

- Gas or liquid storage?
  - High-pressure cylinder storage
  - Cryogenic liquid storage
- Is there a leak or flame present?
  - Gaseous hydrogen: use combustible gas/hydrogen detector and thermal-imaging cameras
  - Liquid hydrogen: look for ice crystals/frozen water vapor
- Is the leak confined by a structure? Ventilation adequate?
- Onsite reforming? Is a methane source present?
- Presence of other fuels (e.g., CNG, propane, gasoline)
- Identify potential ignition sources

Hydrogen Release Indicators

SIZE-UP → PLAN

Compressed H_2

- Very loud hissing (almost all leaks will be audible)
- TPRD[1] release → controlled high-pressure hydrogen rapid release through safety vent
  - Occurs if tanks are exposed to high-temperature heat (e.g., fire)
  - Avoid cutting into hydrogen lines

[1] TPRD – Thermally activated pressure relief device

Hydrogen Lines and High Voltage Systems

SIZE-UP → PLAN

- **Avoid** cutting into hydrogen lines, storage tanks or PRD vent lines
  - No standard markings
  - Most hydrogen fuel lines are silver, stainless steel
- **Do not** cut high-voltage cables
  - Orange in color per SAE standard
  - 200 to 500 volts; 200 to 300 amps

Power Unit and Fueling Trailer Incidents

ACT

- Determine if currently assigned personnel and resources will be adequate
- Request additional resources early in process to ensure timely deployment
- For personnel assigned to an individual task, maintain proper span of control (3 to 7 people)
- Assign tactics/tasks

Photo: Volpentest HAMMER Federal Training Center

Contact Information

Please let us know if you have any questions or comments!

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Hydrogen Storage Tank Specifications

- 15 Type 3, Dynecell tanks designed specifically for use with gaseous hydrogen
- 6061 aluminum (low corrosion) liner with carbon fiber overwrap → Low risk of corrosion due to carbon fiber wrap composite
- Dynecell cylinders certified and operating in: Fuel Cell buses (CUTE, Olympics), Fuel Cell vehicles (Hyundai, Ford, Daimler, Nissan), mobile refueling stations, stationary storage and bulk-hauling applications.
- Each cylinder equipped with its own thermally activated pressure relief devices (TPRD) at each end of the tank (2 per tank)
- Certified to ISO 11439, NGV2, CSA B51, approved by TUV
- Not DOT (not intended for bulk shipment of hydrogen)
- Maximum service life of 15 years, 350 bar/ 35 MPa (5,075 psig)
- Each tank equipped with and integrated TPRD
- Safety Pressure relief device operating on the 100 psi line

Attachment C

"Hydrogen Fuel Cell Demonstration Project at Port of Honolulu"

MarFC Project summary sheet (1) prepared by SNL staff for handouts at training

Maritime Hydrogen Fuel Cell

Safety Features Integrated into Design and Use of System

Safety is the First Priority

The project team completed a number of overlapping safety methods to assure the safety of individuals operating and in proximity to the hydrogen fuel cell including:

- Failure Mode Effects Analysis (FMEA) which identifies potential failure points and devises ways to mitigate them (engineered and administrative/operational controls).
- Independent review and approval of the design by the Hydrogen Safety Panel and the US Coast Guard, and informational review by the American Bureau of Shipping.
- Special consideration of how Young Brothers, Ltd. intends to use the generator.

The fuel cell generator's design has been independently reviewed and approved by the US Coast Guard and the Hydrogen Safety Panel.

Generator Safety Features

Using the FMEA results, a number of safety features or engineered controls were built into the final design based on these core principles:

1. Not allowing accumulation of a hazardous amount of hydrogen.
2. Minimizing stored energy and ensuring releases are non-hazardous.
3. Preventing damage by external events.

The generator's safety features are listed below *(with the design principle(s) addressed in parenthesis)*.

- Redundant hydrogen and smoke detectors shut down the system and sound a loud audible alarm if a leak or fire is detected. These detectors can be left on when the generator is not running. (1)
- Everytime the generator is started, multiple automated hydrogen leak checks occur. The system shuts down if leaks are detected.(1)

One safety feature of the generator is to have redundant hydrogen sensors, including the one shown here, which automatically shut down the generator and close all hydrogen tanks as soon as a hydrogen leak is detected.

- Constant forced-air ventilation throughout the generator room with automatic shutdown in case of ventilation failure. (1)
- Automated hydrogen tank valves require power to open. Any power failure or emergency stop causes these valves to immediately close. (1)
- Two open sides and a slanted roof in the hydrogen storage area provide passive ventilation and dissipation of leaks. (1,2)
- Fire-wall separation of the hydrogen storage from the generator room. (1, 2)
- Five fail-closed valves must be open before hydrogen can reach the fuel cell. (1,2)
- Flow-restricting orifice reduces hydrogen leakage in case of pipe breakage. (1,3)
- Minimized high pressure hydrogen piping, including zero high pressure piping in the generator room. (2)
- Redundant pressure safety devices prevent high pressure from reaching the low pressure piping or the generator room. (2)

- Hydrogen tanks have thermal pressure relief devices that open if a fire is detected, eliminating possibility of tank explosion. (2)
- Ultracapacitor is automatically discharged whenever the unit is turned off. (2)
- Hydrogen releases are directed upward and away from personnel. (2)
- The operator interface is on the far end away from the hydrogen storage area. (2)
- The hydrogen storage tanks are the same used in hydrogen fuel cell cars / buses and built to withstand impact. (3)
- Reinforced sides reduce the chance of a forklift piercing the container wall. (3)
- The container's fork pockets are closed and the container must be mounted on a platform or handled with a top-pick. (3)

Operational Safety Controls

Leveraging Sandia's expertise in hydrogen system risk analysis coupled with Hydrogenics' commercial product design experience, a safety plan for use and handling of the fuel cell generator was defined. This plan identified operational scenarios specific to Young Brothers, Ltd. including: damage to the generator by forklift, blockage of the ventilation system by other containers, and discharge of hydrogen out the relief valve vents.

Site-specific administrative controls were added to the safety plan including these controls:

- Handling with a forklift is acceptable, handling with a top-pick is preferred as it will reduce the likelihood of damage that results in equipment downtime.
- Allow at least two feet of separation between the generator's access door side and adjacent container or structure when operating.
- Workers can transit the zone of potential hydrogen release (see chart and table) but if individuals need to linger within the zone then the generator should be re-oriented.
- In the case of fire in or around the generator, workers should not enter the zone of potential hydrogen release.

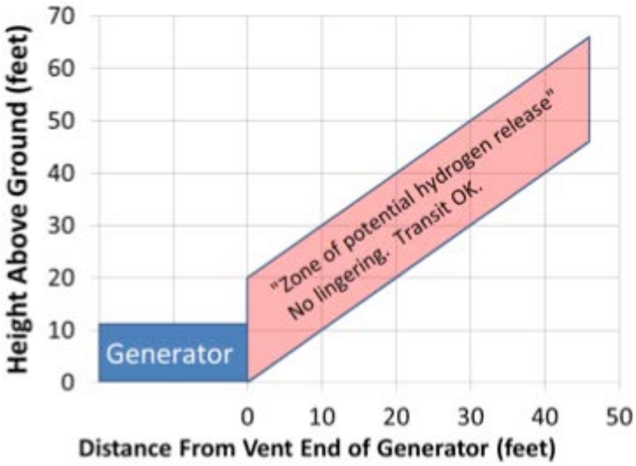

Chart showing the zone of potential hydrogen release from the end of the container with the relief valve vents.

If someone is lingering this far away from the container...	They should be lower than...	Or higher than...
0 feet	should not linger under the vent openings	20 feet
10 feet	10 feet	30 feet
20 feet	20 feet	40 feet
30 feet	30 feet	50 feet
40 feet	40 feet	60 feet
50 feet	N/A	N/A

Table showing recommended locations for personnel lingering directly off the relief vent end of the generator.

For more information please contact:
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Attachment D

"Safety Features Integrated into Design and Use of System"

MarFC Project Summary Sheet (2) prepared by SNL staff for handouts at training.

Maritime Hydrogen Fuel Cell

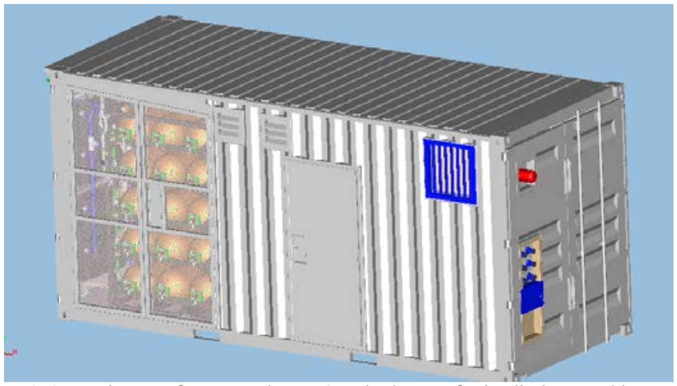
Hydrogen Fuel Cell Demonstration Project at Port of Honolulu

Hydrogen fuel cells have a long track record of supplying efficient, emissions-free power for a wide range of applications, including mobile lighting systems, forklifts, emergency backup systems, and vehicles. The Maritime Fuel Cell Project seeks to add another application to that portfolio, maritime power, by demonstrating a hydrogen fuel cell deployment in a commercial port setting.

The two year project culminates in late 2015 with a six-month demonstration and validation pilot hosted by Young Brothers, Ltd., at their facility in the Port of Honolulu. The pilot hydrogen fuel cell unit will be used in place of a diesel generator currently used to provide power for refrigerated containers on land and on transport barges.

Hydrogenics Corp. is designing and manufacturing a containerized 100-kilowatt hydrogen fuel cell package, which includes the fuel cell engine, a hydrogen storage system, and power conversion equipment built into a standard shipping container, with outward appearance and functionality similar to currently-used maritime diesel generators.

Traditional maritime diesel generator deployed at Port of Honolulu by Young Brothers, Ltd. Photo courtesy of Young Brothers, Ltd.



Artistic rendering of proposed maritime hydrogen fuel cell, designed by Hydrogenics Corp. Image courtesy of Hydrogenics Corp.

The pilot hydrogen fuel cell unit will be deployed in the Port of Honolulu by project partner, Young Brothers, Ltd., a subsidiary of Foss Maritime Company. As the primary inter-island shipper of goods within Hawaii, Young Brothers, Ltd. has a strong environmental and financial interest in the project. Initially the unit will be used on land and later will be deployed on-board barges traveling between the Port of Honolulu and Port of Kahului, in both cases providing power so refrigerated containers keep their perishable contents cold throughout the journey.

During the 6 month demonstration, performance feedback and data will be collected to determine the environmental, energy and cost savings from the unit. Sandia will analyze the operational, safety and cost performance data to develop a business case for using hydrogen fuel cells at other ports. Feedback from stakeholders on the design and operation may guide regulators toward formal codes and standards for hydrogen and fuel cells in maritime applications which will increase adoption of this clean energy technology.

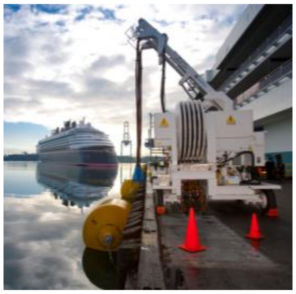
Project Partners

Sandia National Laboratories provides the overall project leadership and coordination services for the 12-partner team as well as lending its unique expertise in hydrogen materials, systems, and risk analysis, and codes and standards development. Sandia is also responsible for hydrogen supply and delivery coordination and will be providing independent technical and business-case analysis.

Other partners include the Department of Energy's (DOE's) Fuel Cell Technology Office (part of the Office of Energy Efficiency and Renewable Energy) and the Department of Transportation's Maritime Administration, which are sponsoring the project, as well as Hawaii Natural Energy Institute, which will assist with hydrogen supply issues, the Hawaii Center for Advanced Transportation Technologies, which is providing the hydrogen for the duration of the demonstration, and Pacific Northwest National Laboratory, which is conducting hydrogen safety training for personnel and first responders. Also involved are the Hydrogen Safety Panel, the U.S. Coast Guard and its local Sector Honolulu office, and the American Bureau of Shipping, all of which are independently reviewing the safety aspects of the design and operating plans and which see the project as a step toward formal regulations for hydrogen and fuel cells in maritime applications. Each partner has contributed significant time and/or equipment to the project at their own cost.

Environmental Impact Benefits

Major ports can produce daily emissions equal to those of half a million cars or more, many U.S. ports have begun to adopt green practices to combat these environmental impacts. Hydrogen fuel cells have the potential to meet the electrical demands of vessels in the port as well as supply power for other port uses, such as yard trucks, forklifts and other material handling specialty equipment. Hydrogen fuel cells produce zero pollutant emissions and no greenhouse gases at the point of use and can reduce the overall amount of diesel or other maritime fuel used.



U.S. DEPARTMENT OF ENERGY
Sandia National Laboratories
YOUNG BROTHERS Your Neighbor Island Partner
FOSS
HYDROGEN Safety Panel
HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD
ABS FOUNDED 1862 AMERICAN BUREAU OF SHIPPING & AFFILIATED COMPANIES
HNEI Hawai'i Natural Energy Institute University of Hawai'i at Mānoa
PREVENT RESPOND PREPARE SECTOR HONOLULU

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Attachment E

A selection of attendee Questions and Comments discussed at some of the training sessions.

1. Diesel generator sets are placarded Flammable 2. Will the MarFC unit have DOT placarding?

2. Container labeling is on sides, and could (will) be obscured by other containers. Can graphics (e.g. DOT labels) be added to ends to help identify the unit and hazards?

3. Are coolant radiator fans explosion-proof (intrinsically safe)?

4. Where is alarm horn for smoke alarm and hydrogen sensors? Are sounds unique – can they be differentiated? How loud are they? (Coast Guard says there are decibel requirements for alarms to be audible over ambient noise).

5. If the H_2 sensor alarms (horn), will one know if it is from the storage or generator room?

6. Is there a local status indicator of 24V battery charge? (Comment: "so once the battery is dead, the unit is dead?")- confirmed with Hydrogenics that a 24 volt energy supply would be needed to start the unit, which requires access to the generator room.

7. Will Knox box be keyed so either port (HFD or MFD) can access? Decision has since been made to put a padlock on the door that a responder can cut off if necessary, eliminating the need for a Knox box.

8. YB personnel said cargo arrives at destination islands with a heavy coating of salt from spray. Sometimes waves break over sides of vessel. Comment that "splash guards" may be ineffective. What would be effect of salt spray in generator room?
    a. Are there filters for salt for the FC intake?
    b. The Hydrogen Safety Panel had apparently commented earlier on salt effects on stainless steel tubing, etc.

9. YB recommendation: For handling, unit should probably not be "top-picked", but instead be placed on "platform" (flat pallet?). Top-picking machine requires lots of room to maneuver. Preferred location of unit may require forklift for manueverability, therefore use the platform.

10. YB Union Rep: "ALL employees need training for operations of this unit. Can't expect that few trained employees will always be available when needed. The expectation of tracking trained personnel and limiting their use/exposure to those 'trained' is unrealistic."

11. Coast Guard believes they will have jurisdiction of unit once in operation. Who is responsible for container inspections, especially fuel tanks?

12. Are lights on user interface LEDs or filament with backup? If they are filament lights, can a light burnout and the system still run?

13. Are there to be additional labels and simplified operating instructions at the user interface?

14. Will the Coast Guard be able to access information, such as from the system controller or telemetry, if alarms sound or a major accident occurs? (They will ultimately if an incident occurs, but easier if they have access in the first place).

15. Can the unit take starting up with the reefers plugged in and 'on', or will it send it into a fault? The plug-ins on the diesel generator sets all have individual breakers.

16. A concern was expressed from the ABS representative: "With typical use and environmental exposure, will the switches, etc. be the early failure components?

17. Does the project anticipate having Lock-Out/Tag-Out requirements for the equipment during the demonstration phase that may be different from YB procedures?

18. Will there be a Notification Tree established and readily available for incidents?

Attachment F

Attendee lists for each of the training sessions in Honolulu and Kahului.

NOTICE

Attachment F deleted to protect the privacy of attendees. Refer to Section 3 "Training Statistics" on page 9 of the body of the *Final Report: Maritime Fuel Cell Project Hydrogen Safety and Emergency Response Training Honolulu, Oahu and Kahului, Maui – Hawaii* (Appendix D of the *Maritime Fuel Cell Generator Project* report for information about attendance at the training sessions.

Appendix E

MarFC Generator Periodic Checkout Log

MarFC Generator Periodic Checkout Log

WEEKLY OR AFTER EACH BARGE TRIP

External walkaround

Y	N		Y	N	
☐	☐	Damaged control panel	☐	☐	Damaged gauges or covers
☐	☐	Damaged plug(s)	☐	☐	Damaged radiator louvers
☐	☐	Damaged side vents/louvers	☐	☐	Skin dents more than 2” deep
☐	☐	Damaged doors	☐	☐	Damaged/missing fill port covers

Describe:

Internal inspection – generator room

Y	N		Y	N	
☐	☐	Loose items	☐	☐	Missing/open lock-out locks
☐	☐	Coolant leaks	☐	☐	DI water below “Full When Cold” line
☐	☐	Pooled water	☐	☐	Coolant pressure < 10 psi

Shock indicators – Read and RESET

Wall:	☐ 2G	☐ 4G	☐ 6G	☐ 8G	☐ 10G
FC Rack:	☐ 2G	☐ 4G	☐ 6G	☐ 8G	☐ 10G

(2G and 4G shocks do not require additional inspection prior to return to service)

Describe:

MONTHLY (first day of each month)

Inspect and remove the panel near the bottom of the hydrogen storage room and open the doors. In the hydrogen storage room look for:

- ☐ Panel/gauge damage
- ☐ Pooled water
- ☐ Corroded/brown piping or supports
- ☐ Loose items

Describe:

Recorded by:___________________________ Date:______________ Time Spent:_______________

Appendix F
MarFC Generator Daily Usage Log

MarFC Generator Daily Usage Log

Date:________________________ Location:_______________________________________

Reefer 1: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint	Reefer 2: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint
Reefer 3: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint	Reefer 4: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint
Reefer 5: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint	Reefer 6: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint
Reefer 7: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint	Reefer 8: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint
Reefer 9: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint	Reefer 10: Time On/Off: _________/_________ ☐ 20’ ☐ 40’ | ☐ ThermoK ☐ Carrier ☐ Frozen ☐ Chill | ☐ Warm ☐ At Setpoint

☐ Incident? (Fill out YB Incident Report)

☐ Hazard/Near Miss/Non-Start/Auto Shutdown/Alarm? (Fill out YB Near Miss & Hazard Observation Report)

Data taken by:____

Appendix G

Young Brothers *Incident Report*

INCIDENT REPORT

GENERAL INFORMATION.

Company: ☐ FOSS - Hawaii Regiion ☐ Young Brothers, Limited

Type of Incident:
☐ Injury/Illness ☐ Machinery Failure or Damage
☐ Environment ☐ Third Party Property Damage
☐ Cargo Damage ☐ Equipment or Hull Damage

Date of Incident:____________ Time:________Terminal/Vessel:_____________Supt: ________________

INCIDENT INFORMATION.

Injured Employee - Customer Injury - Property Damage

Name: ____
Address: ____
Telephone No.: ____
Injury/Damage Type: ____

Injury: ☐ 1st Aid Only ☐ Sent to Clinic/Hospital Drug Test ☐Yes ☐No

---

HTB/YB Personnel Involved
Name and Position

____
____
____
____
____

Machinery Failure or Damage

Description of equipment involved: ________________________________
Type of damage: ________________________________

☐ Total Loss ☐ Repairable

CD:
Shipper: ________________________________
Consignee: ________________________________
B/L No.: ________________________________
Type of damage: ________________________________
Disposition of Damage Cargo ________________________________
Extent of Damage ________________________________

INCIDENT Description

PERSON DIRECTLY INVOLVED *(Describe what happened and draw any diagrams that will help)*:

____
____
____
____
____
____
____
____

Print Name: ____________________ Signature:______________________ Date:_________

Drawing or Diagram (attach photos if possible)

WITNESS *(Describe what you saw)*: Use Witness form if multiple witnesses

____

____

____

____

____

Print Name: ____________________ Signature:_______________________ Date:_________

SUPERVISOR: *Contributing factors to the incident*

____

____

____

____

____

Print Name: ____________________ Signature:_______________________ Date:_________

<u>INSTRUCTIONS</u>.

1. Complete the Incident Information for **all** incidents **and** the specific section for the type of incident you are reporting.
2. Provide as much **detailed** information as possible in the Incident Description
3. Send the **Incident Report** to Safety Manager and your Department Manager.
4. Be sure the report is signed and dated by everyone completing a section.
5. **All** incidents **must** be reported **Immediately** Incident Report **must** be submitted before end of shift or within **12 hours** for marine incidents.

Appendix H
Young Brothers *Near Miss & Hazard Observation Report*

SAFE! ALWAYS

03.01 Near Miss & Hazard Observation Report

This form is for reporting a Near Miss or Hazard Observation event. If there was an accident or injury please complete the appropriate forms and scan a copy to nkapule@htbyb.com.

Completion of this form is recommended any time a hazardous condition exists or when there is a near miss event. Examples of hazard observation include: broken stairs, broken/missing hand/guard rails, potholes, dangerous procedures, etc. A near miss is an event where you almost got into an accident, damaged something, or injured but luckily did not. Lessons learned from these events can help everyone avoid them in the future.

☐ Hazard Observation	☐ Near Miss	**000-14**
Name:	Employee / Customer Circle	Report Date:
Date of event or discovery of condition:	Time of event or discovery:	
Location:	Area at Location:	

Describe Near Miss or Hazard Observation: (Include as much detail as possible to aid in determining the root cause so that appropriate action can be taken. If more space is required please attach the supplemental form.)

This section to be completed by Supervisor or Manager

Name:	Position Title	Date:

Describe the root cause and action taken to remove / reduce risk. If unable to accomplish locally what support will be required to remove / reduce risk: (Attach supplemental forms as necessary.)

Corrected By:

Photos Attached: ☐ Yes ☐ No	**Assigned To:**	Supplemental Form(s) Attached: ☐ Yes ☐ No	Total # of pages:

Forward completed form(s) to the Safety & Environmental Manager

SAFE! ALWAYS

Page ___ of ___

Name:	Employee / Customer Circle	Report Date:

Photos Attached: ☐ Yes ☐ No	**Assigned To:**	Supplemental Form(s) Attached: ☐ Yes ☐ No	Total # of pages:

Appendix I

Young Brothers *JSA 034 – Job Safety Analysis Form – Loading Generator on Barge*

JSA 034 – Job Safety Analysis Form – Loading Generator on Barge			
Job Title: Machine Operator	**Job Location**: Loading GEN on Barge	**Analyst:** Safety Manager	**Date:** MAR 2015

Task # 034 Loading Generator on Barge	**Task Description: Loading Generator on Barge** 1. With a 20-ton Forklift machine, pick up 20' Generator 2. Transport generator up barge ramp 3. Place Generator in designate location on barge,
Hazard Type	**Hazard Description:** 1a. 20-ton Forklift Machine Failure 1b. Operator Struck By other vehicle in traffic lane 1c. Injury to MO while operating and picking up 20' Generator 1d. Slip Trip and Fall while gaining access to forklift 1e. Forklift not capable of lifting generator 2a. Jolting from driving over uneven surface 2b. Noise Hazard due to engine and reverse alarm volume 2c. Generator damaged due to design flaw of Generator unit 3a. Uneven weight distribution of cargo 3b. Damage to Generator when placing in designated location
Controls and Preventive Measures	**Hazard Controls:** 1a. Perform pre-inspection of forklift, report discrepancy to supervisor 1b. Machine Operator shall don proper PPE 1c. Position in machine operator's seat, 1d. 3-point contact climbing into forklift cab and wear seat belt 1e. Assure forklift is able to lift the generator safely, check name plate 2a. From seated position in cab, visually survey generator and pier surface 2b. Wear hearing protection while operating 3a. Confirm load is stable and safe to transport from staging area to barge 3b. Lift, tilt, and proceed to transport cargo up to and onto barge 3c. Use mirrors, horn, lift lever and tilt lever appropriately. 3d. Do not exceed the 5 to 10 mph speed limit, 3e. Park in designated parking area, lower load, set hand break, turn off the motor, and maintain 3-point contact while getting off FL. 3f. Constantly survey immediate area for unsafe conditions

Rational or Comment: Step 1. Perform pre-inspection and report any problems to supervisor Step 2. Plan your operation with 3-point entry into operator's seat Step 3. Assure load is safe to lift and transport, lift, tilt and look in the direction you are traveling Step 4. Low load, set hand brake, turn off motor, before dismounting forklift. Note: Notify immediate supervisor if unsafe conditions are found

Save JSA in the following Folder: S:\Safety-Environment\7.00 Job Safety Analysis\JSA

Appendix J
Weather Summary

Table J-1: Weather conditions for operating days

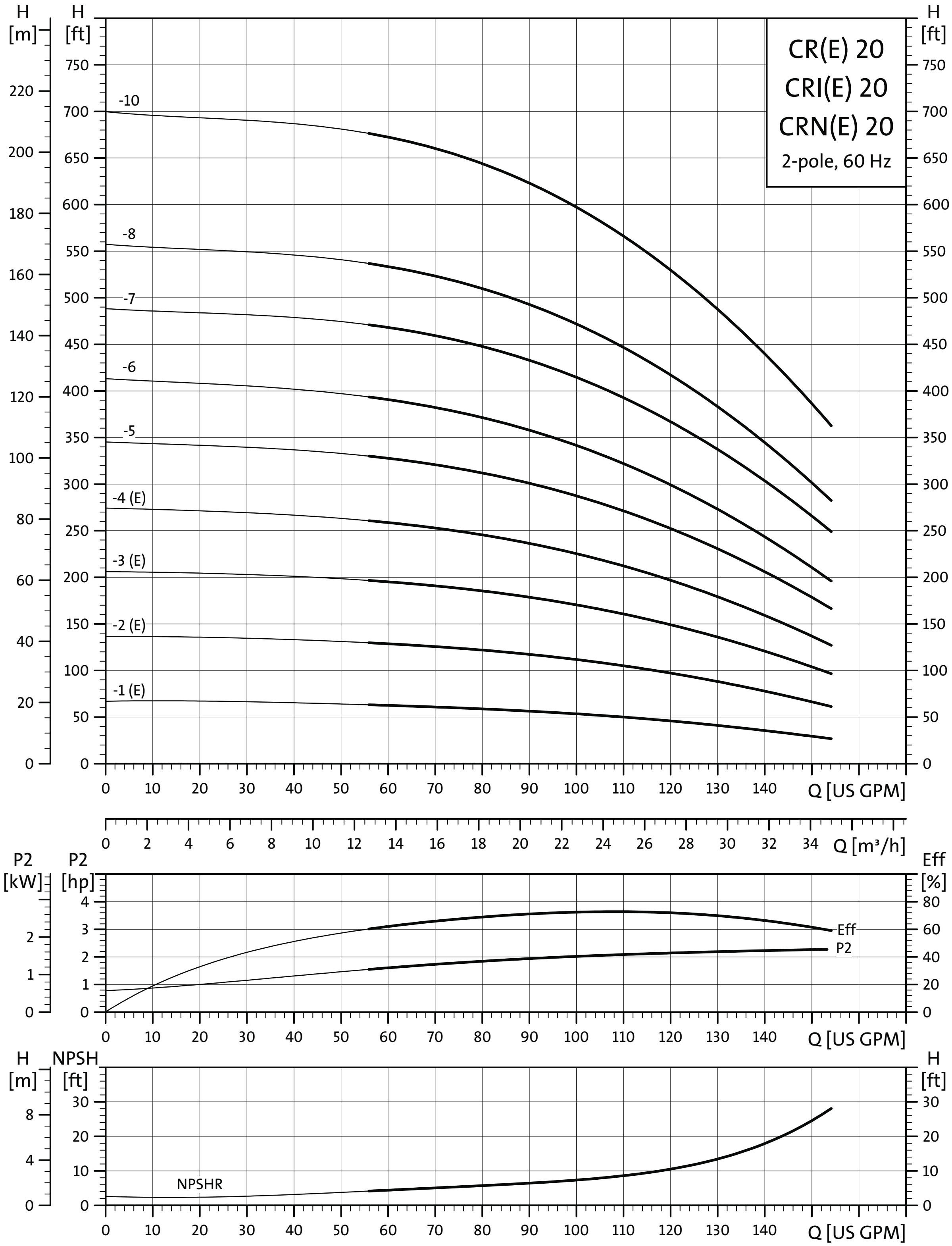
Date	Weather Conditions			
Date	Avg. Temperature	Avg. Relative Humidity	Windspeed	Conditions
MM/DD/YY	deg F	%	mph/direction	Example: Sunny, Rain, Overcast, Foggy, Cloudy
8/4/15	86.37	59.66	13.03/ENE	Scattered Clouds
8/6/15	83	70	7/N	Mostly Cloudy
8/7/16	84	75	10/E	Mostly Cloudy
8/10/15	88	50	17/NE	Scattered Clouds
8/11/15	80.025	74.75	6.93/E	Scattered Clouds
8/11/15	88.36	56	13.07/ENE	Mostly Cloudy
8/11/15	89.37	52.33	13.06/E	Scattered Clouds
8/12/15	86	64	10/ENE	Scattered Clouds
8/13/15	86	63	12/ENE	Mostly Cloudy
8/19/15	82	77	4/SSE	Scattered Clouds
8/20/15	84.27	72.43	8.9/SSE	Scattered Clouds
8/20/15	86	63.5	9.225/SE	Scattered Clouds
8/25/15	82.3	83	9.23/S	Mostly Cloudy
8/25/15	80.3	92.75	10.1/SE	Rain
8/26/16	78.5	83.5	3.5/NE	Scattered Clouds
8/27/16	81	84	3/NNW	Light Thunderstorm/Rain
8/28/16	85.775	71.25	7.5/SSE	Scattered Clouds/Mostly Cloudy
8/28/16	86	65	11/NNE	Mostly Cloudy
09/14/15	84	72	9/NE	Scattered Clouds/Mostly Cloudy
09/15/15	82	78	7/NE	Mostly Cloudy
09/16/15	84	66	8/NE	Scattered Clouds
09/22/15	86	64	13/ENE	Scattered Clouds
09/23/15	84	65	8/NE	Mostly Cloudy
09/24/15	84	66	8/ENE	Scattered Clouds
10/5/15	81	77	5.8/N	Mostly Cloudy
10/7/16	81	62	4.6/NNE	Scattered Clouds
10/9/15	84	64	6/NE	Scattered Clouds
10/16/15	89.1	56	12.2/NE	Scattered Clouds/Mostly Cloudy
11/13/15	79	67	13/ENE	Mostly Cloudy/Light Rain
1/7/16	76	69	4/NNE	Scattered Clouds
2/10/15	71	69	6/NW	Scattered Clouds
2/12/16	78	65	8/E	Scattered Clouds
2/13/16	79	70	8/ENE	Scattered Clouds

Date	Weather Conditions			
Date	Avg. Temperature	Avg. Relative Humidity	Windspeed	Conditions
MM/DD/YY	deg F	%	mph/direction	Example: Sunny, Rain, Overcast, Foggy, Cloudy
2/16/16	75	65	15/NE	Cloudy/Light Rain
2/22/16	73	62	9/NNW	Clear/Scattered Clouds
3/4/16	73	73	6/WNW	Scattered Clouds/Haze
3/7/16	75	76	5/SSE	Mostly Cloudy
3/9/16	72	52	14/NNE	Scattered Clouds
3/11/16	75	59	18/ENE	Scattered Clouds
3/18/16	73.55	62.75	12.1/NE	Scattered Clouds
3/18/16	78	48	18.4/NNE	Scattered Clouds
3/29/16	82	76	13/W	Scattered Clouds
3/30/16	82	68	6/WNW	Scattered Clouds
3/31/16	82	73	6/ENE	Scattered Clouds
4/1/16	82	71	6/NW	Scattered Clouds
4/4/16	82	74	6/S	Scattered Clouds
4/8/16	84.9	53	16.1/ENE	Scattered Clouds
4/12/16	83	61	16/NE	Scattered Clouds
4/22/16	82	54.3	15.3/ENE	Scattered Clouds
4/23/16	80	64	9.8/E	Mostly Cloudy
4/27/16	83	65	14/ENE	Scattered Clouds
4/28/16	77	57	13/ENE	Scattered Clouds
4/29/16	77	64	10/ENE	Scattered Clouds
6/7/16	81	49	23/NE	Scattered Clouds
6/8/16	80	60	9/ENE	Partly Cloudy/Scattered Clouds

Appendix K

Coolant Pump Curve (Grundfos CRE20-2)

CR(E), CRI(E), CRN(E) 20



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