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# Maritime Fuel Cell Generator Project: 2018 – 2023

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Photo courtesy of Bruce Appelgate, Scripps Institution of Oceanography

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# ABSTRACT

This report summarizes activity in the Maritime Fuel Cell (MarFC) Generator Project from 2018 – 2023. FY 2018 saw the implementation of upgrades and repairs, making the unit more reliable and operator friendly. In FY2019 the team engaged the Scripps Institution of Oceanography (SIO) to use the MarFC to provide zero-emission shore power to the research vessel R/V *Robert Gordon Sproul* while in port at the Nimitz Marine Facility in San Diego, CA. In FY2020, the MarFC unit was shipped to San Diego, CA. A fueling contract with IGX was established to support MarFC operations at SIO, with renewable hydrogen provided by the California State University Los Angeles (CSULA) hydrogen station.

The project team (Sandia, Cummins/Hydrogenics) provided training to SIO staff on the technical details of the MarFC, the safe use of hydrogen in general and the MarFC in particular. The first fueling of the unit at the SIO pier was successfully completed by IGX. The first powering of a vessel with fuel-cell shore power was conducted with the R/V *Robert Gordon Sproul*. While the mechanical systems (lights, AC, ventilation, hydraulics, pumps and cranes) were powered without incident, problems arose when powering the computer systems, which were traced to a grounding issue within the MarFC. Inspections carried out in FY2021 revealed the MarFC needed routine maintenance. Maintenance was performed and the unit was upgraded. The MarFC was turned on after the year pause, and initial test data on power levels and stability were collected. FY2022 was a year spent repairing, upgrading and testing the MarFC unit. Spikes in power and voltage were observed above 60 kW that could potentially extend below 60 kW with time. Such spikes could cause problems with the *Sproul* electrical systems. These age-related problems, the extended time for the *Sproul* spent in dry dock for scheduled upgrades, and the associated need to reschedule the vessel's high-priority science missions made it no longer possible to deploy the unit at SIO.

After discussion, the decision was made by DOE, MARAD and the project team to cease the deployment, remove the MarFC from SIO, and not pursue further deployment activities. On December 2, 2022, the MarFC unit was removed from the Scripps Nimitz Marine Facility and shipped to Fridley, Minnesota. The Cummins/Hydrogenics plan for the unit is to assess the condition of the MarFC subcomponents, and then use it as a training/learning system for technical employees new to hydrogen fuel-cell technology.

After summarizing project activity from 2018 – 2023, this report provides a review of lessons learned and next steps in contemplating a follow-on project that would further advance the use of fuel-cell-based shore power in a marine setting. A comparison is made of the project results to the original objectives. This report concludes with an accounting of presentations stemming from the project, and a list of references.

# ACKNOWLEDGEMENTS

Funding of this work was provided by The U.S. Department of Transportation's Maritime Administration via MARAD's Maritime Environmental and Technical Assistance (META) program. The author thanks Sujit Ghosh (retired) and Bryan Vogel at MARAD for their encouragement of the work and providing project management from the MARAD side. Thanks are extended to Michael Carter and Dan Yuska of MARAD for their on-going support of the hydrogen maritime studies at Sandia.

Funding for this work also came from the U.S. Department of Energy (DOE) Hydrogen Fuel Cells Technologies Office (HFTO) under their Market Transformation program. The author thanks Pete Devlin at DOE for his encouragement, advice and project management from the DOE side. Charlie Meyers, subcontractor to DOE provided on many occasions support and ideas for deployment for which the author is grateful. Thanks are also extended to Sunita Satyapal of DOE for her ongoing support of hydrogen technology studies at Sandia.

During the course of this work, the author received wise counsel from his Sandia managers, first Jon Zimmerman followed by Joe Ronevich and Kristin Hertz. Sandia legal support from Madelynne Farber was much appreciated. Wendy Dolstra provided administrative support for the subcontract with Cummins/Hydrogenics. The author thanks Joe Ronevich of Sandia for a very thorough and constructive review of this report.

Joe Pratt was the original Sandia lead for this project before he left to start Zero Emission Industries (formerly Golden Gate Zero Emission Marine). On many occasions, Joe would give very useful advice on the conduct of the project. His counsel and friendship are much appreciated. Shun Yuk Chan was also a leader of this project over the period 2014 – 2018.

Since 2018, many people have contributed to the planning and execution of this project. Ryan Sookhoo from Hydrogenics (later Cummins/Hydrogenics) was in most ways a co-leader of this project with me. Ryan's wise technical direction, and follow-through on repairing and upgrading the MarFC was essential to project progress. Other contributors from Cummins/Hydrogenics include Austin Mattison, Sagar Sharma, Luis Orosco, Al Reeves, Ed Pax, Jayant Arora, Max Muller, Dave Haywood, Will Cook and Nader Zaag.

The last phase of the project involved deploying the MarFC at the Scripps Institution of Oceanography in San Diego. SIO was a remarkably supportive deployment partner, and generously allowed the team to attempt to power one of their valuable and heavily scheduled research vessels with the MarFC. SIO also helped support the project technically (wiring, cable creation) when we first attempted to power the R/V *Robert Gordon Sproul*. During the Covid-19 pandemic, when SIO was trying to figure out how to operate their research vessels on international voyages during a pandemic, they were still generous with their time in discussing our deployment project. Special thanks go to Bruce Appelgate, the Associate Director of SIO, who was a close collaborator on the project. We thank Marine Superintendents Zoltan Kelety, Eric Buck and Joost Van Der Zwaag for helping with the logistics of delivering, placing and ultimately removing the MarFC from the Nimitz Marine Facility, and Andrea Lupu for working out the legal aspects. Zoltan also provided the international standard for high-voltage shore connectors, IEC/IEEE 80005-1:2019 as a check for MarFC compatibility with industry standards. Captain Chris Welton, skipper of the *Sproul*, was a very technically savvy supporter of the initial *Sproul* powering and worked with us to assess the extent to which the powering was successful. *Sproul* crew members Paul Mauricio, Ernesto Bayer and James McManus are thanked for helping with the initial scoping assessment and eventual powering of the *Sproul*.

No hydrogen fuel-cell deployment project can exist without a source of hydrogen. Thanks are extended to DeLisa Leighton, Michael Koonce and Craig Van Pelt of IGX for their many contributions in providing hydrogen to the project. DeLisa in particular was very pro-active making connections to the project with local stakeholders in government (Camp Pendleton), industry (SoCal Gas) and academia (UCSD, CSULA). The role played by the CSULA Hydrogen Station led by Michael Dray for making the hydrogen used in the project was vitally important.

Although the project did not end up being deployed there, the folks at Curtin Maritime are thanked for their extensive discussions with the project team. This includes owner Captain Martin Curtin and his colleagues Andrea "Boomer" Sisneros and Marley Schroepfer. Connection to Curtin Maritime was at the recommendation of Christine Houston, Manager of Sustainable Practices at the Port of Long Beach. This guidance is much appreciated. We appreciate discussions with hydrogen suppliers and hydrogen colleagues Roy Bant, Dwight Zuck and Jorge Lopez (Air Liquide), Jeff Earl and James Lohan (Linde) and Chris Kretz (Air Products) who provided support early in the discussions with Massport. Although a legal issue prevented our deployment at Massport, Mike Meyran and Rocco Pompeo of Massport spent many hours with us trying to find a path to deployment.

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# EXECUTIVE SUMMARY

This report summarizes activity in the Maritime Fuel Cell (MarFC) Generator Project from 2018 – 2023. A brief review is given of the project background, including its origins, objectives, a description of the MarFC itself, and a summary of the first deployment period. These earlier activities were fully described in a prior report [1] covering the period 2014 – 2017. This background information is followed by a description of the activity in the second project phase from 2018 – 2023. The MarFC project has been co-funded by the U.S. Department of Energy(DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) and the U.S. Department of Transportation (DOT) Maritime Administration (MARAD).

The project activities and results are presented chronologically by fiscal year (FY) from FY2018 – FY2023, with the FY beginning October 1. The prior deployment in Hawaii [1] pointed to several ways the MarFC unit needed to be improved and items needing repair. These upgrades and repairs were implemented and tested in FY 2018, with the result being a unit that was more reliable and operator friendly.

In FY2019, the team engaged the Scripps Institution of Oceanography (SIO) to use the MarFC to provide zero-emission shore power to the research vessel R/V *Robert Gordon Sproul* while in port at the Nimitz Marine Facility in San Diego, CA. This application was determined to be a good technical use of the MarFC unit and compatible with the applicable legal requirements and NFPA 2 safety regulations. The MarFC unit was upgraded (transformer, connections, internal heaters) to provide 480 VAC operation, as required by the R/V *Robert Gordon Sproul*, with the proper electrical interface box to be compatible with the vessel power cable. Subsequently, at the Cummins/Hydrogenics facility in Mississauga, Ontario, Canada extensive start-stop and endurance performance testing was conducted of the MarFC electrical upgrades in preparation for shipment to San Diego and deployment at SIO.

In FY2020, the MarFC unit was shipped to San Diego, CA. A fueling contract with IGX was established to support MarFC operations at SIO, with renewable hydrogen provided by the California State University Los Angeles (CSULA) hydrogen station. Inspection of the MarFC unit after shipping revealed damage had been sustained in transit to SIO, damage that was repaired onsite by Cummins/Hydrogenics staff. The project team (Sandia, Cummins/Hydrogenics) provided training to SIO staff on the technical details of the MarFC, the safe use of hydrogen in general and the MarFC in particular. The first fueling of the unit at the SIO pier was successfully completed by IGX. The first powering of a vessel with fuel-cell shore power was conducted with the R/V *Robert Gordon Sproul*. While the mechanical systems (lights, AC, ventilation, hydraulics, pumps and cranes) were powered without incident, problems arose when powering the computer systems. In particular, these systems found the MarFC power unacceptable, and battery-based uninterruptable power supply (UPS) systems turned on and were drained. There was some collateral damage to several vessel power supplies as well, which SIO collegially repaired. Cummins/Hydrogenics analysis of the vessel electrical diagram and consultation with subcontractor ABB indicated the problem lay with a MarFC-vessel interface issue, which could be remedied with a suitably placed grounding cable within the MarFC unit. All onsite operations were then suspended for the remaining ~ 8 months of FY 2020 by the Covid-19 pandemic, and up until April of FY 2021.

In FY2021, inspection of the unit revealed the MarFC needed routine maintenance after a year of being turned off with no preparation. Maintenance was performed (coolant, batteries) and the

unit was upgraded (grounding cable). The MarFC was turned on after the year pause, and initial test data on power levels and stability were collected.

FY2022 was a year spent repairing, upgrading and testing the MarFC unit. The fuel cell modules were tuned, hydrogen detectors that had exceeded their calibration/lifetime were replaced, a small hydrogen leak was found and corrected, a bleached-out user interface monitor was replaced, and a remote monitoring (wireless) capability was added to the MarFC unit. Examination of the prior test data, and collection/analysis of subsequent test data indicated the output power needed to be kept below 60 kW. The cause of the 60-kW power limit was two-fold. The first issue was the ultracapacitors installed to handle fast transient loads were degraded and needed to be replaced. As a result, if the unit was operating above 60 kW and a transient needed to be handled, there would be a power instability The second issue was that degradation was seen in the overall fuel cell performance. The source of the degradation is unknown, but perforation or contamination of the proton exchange membrane (PEM) within the modules is suspected.

As a result of these issues, risky spikes in power and voltage were observed above 60 kW that could potentially extend below 60 kW with time. Such spikes could cause problems with the *Sproul* electrical systems. These age-related problems, the extended time for the *Sproul* spent in dry dock for scheduled upgrades, and the associated need to reschedule the vessel's high-priority science missions made it no longer possible to deploy the unit at SIO. While routine use of the MarFC would not inhibit vessel activities at port, the initial phase of the deployment would involve more time from SIO vessel technicians, as it involves data collection and monitoring. After discussion, the decision was made by DOE, MARAD and the project team to cease the deployment, remove the MarFC from SIO, and not pursue further deployment activities. On December 2, 2022, the MarFC unit was removed from the Scripps Nimitz Marine Facility and shipped to Fridley, Minnesota. The Cummins/Hydrogenics plan for the unit is to assess the condition of the MarFC subcomponents, and then use it as a training/learning system for technical employees new to hydrogen fuel-cell technology.

After a Summary of the project activity from 2018 – 2023, this report provides a review of the "Lessons Learned." For example, we learned that the preferred output power for a broadly useful MarFC unit is 480 VAC, and it is paramount to investigate in advance the compatibility of the electrical architecture of the end use. The need for robust and marinized power conditioning electronics are key take-aways from the project. At a higher-level, the cost of hydrogen remains high, which must be explicitly budgeted for in such projects. Another lesson learned is the need for local sources of hydrogen to be able to provide a variety of hydrogen pressures, not just 700 bar for fuel-cell vehicles, but also 350 bar hydrogen for non-vehicle uses of hydrogen such as the MarFC.

This report provides "Next Steps" in contemplating a follow-on project that would further advance the use of fuel-cell-based shore power in a marine setting. For example, it would be necessary to assess the many advances made in fuel-cell technology since the origin of this project in 2013. A review of the application market for zero-emission shore power would need to be conducted, along with an assessment of the design requirements such as the desired power level, the type of fuel cell and the necessary container size. Because we were not able to confirm that a shore side power system could successfully power sensitive computer equipment on-board a vessel, this would be a first goal of any new project aiming to demonstrate shoreside hydrogen fuel-cell powering of vessels.

A comparison is made of the project results to the original objectives. Some of the objectives were met, others not. The project lowered the technology risk of future port fuel-cell deployments (a key objective) by encountering and overcoming technical problems in the operation of the MarFC. The goals of providing validated economic operations and maintenance data for routine use of the MarFC were not achieved due to the lack of long run-time experience with the unit. By acquiring a Design Basis Letter for the MarFC via extensive engagement with the United States Coast Guard (USCG), the project has eased the regulatory approval path for future shore-side power projects using hydrogen fuel-cell technology. A key project objective was to spread the benefits of hydrogen fuel-cell technology to the community of maritime end users. Along the way, a variety of potential end users were engaged, which had the effect of informing the community about stationary shore power based on hydrogen PEM fuel-cell technology.

This report ends with an accounting of presentations stemming from the project and a list of references.

## ACRONYMS AND TERMS

| Acronym/Term | Definition |
|---|---|
| ABS | American Bureau of Shipping |
| CSULA | California State University Los Angeles |
| DOE | Department of Energy |
| DOT | Department of Transportation |
| FY | Fiscal year |
| HFTO | Hydrogen Fuel Cell Technologies Office |
| MARAD | Maritime Administration |
| MarFC | Maritime Fuel Cell |
| META | Maritime Environmental and Technical Assistance |
| NFPA | National Fire Protection Association |
| Massport | Port of Massachusetts |
| PEM | Proton exchange membrane |
| R/V | Research vessel |
| SIO | Scripps Institution of Oceanography |
| SIM | Subscriber identity module |
| USCG | United States Coast Guard |
| UCSD | University of California San Diego |
| UPS | Uninterruptable power supply |

# 1. INTRODUCTION

This report summarizes activity in the MarFC Project during the period 2018 – 2023. The project, initiated in 2013, had the following overall aims:

- Lowering the technology risk of future port fuel-cell deployments by providing performance data of hydrogen PEM fuel-cell technology in this environment.
- Lowering the investment risk by providing a validated economic assessment for this and future potential projects.
- Enabling easier permitting and acceptance of hydrogen fuel-cell technology in maritime applications by assisting the USCG and the American Bureau of Shipping (ABS) in developing hydrogen fuel-cell codes and standards.
- Engaging potential adopters/end users of hydrogen fuel cells to enable more widespread acceptance of the technology.

The project origins, MarFC design and construction, approval by the USCG, and first deployment have been described in detail in a prior document covering the period 2013 – 2017 [1]. This report provides a brief review of the project background and origins, a description of the MarFC itself, and a summary of the first deployment period. This background information is followed by a description of the activity in the second phase of the Maritime Fuel-cell Generator Project from 2018 to 2023. Both HFTO and MARAD have co-funded the project since its inception. Cummins/Hydrogenics was the MarFC system supplier.

# 2. BACKGROUND (2013 – 2017)

Greenhouse gas and criteria pollutant (i.e., smog) emissions in maritime ports are an opportunity for transportation energy efficiency improvements and emissions reduction efforts. Ocean-going vessels, harbor craft, and cargo handling equipment constitute major sources of diesel-based emissions at ports. Hydrogen fuel cells have an established track record of supplying efficient, clean power for a wide range of applications, including forklifts [2], mobile lighting [3], buses [4][5], and light-duty vehicles [6], replacing the incumbent and polluting diesel-based combustion technology. The MarFC Project investigates the prospects for replacing this incumbent technology for shore-power systems.

The MarFC project developed and demonstrated a 100 kW, integrated fuel-cell prototype for marine applications, depicted schematically in Figure 1. Hydrogenics Corporation (purchased by Cummins in 2019, and hereafter referred to as Cummins/Hydrogenics) designed and built a containerized 100-kW hydrogen fuel-cell unit, which included a PEM fuel-cell engine, a hydrogen storage system (350 bar compressed gas, 67 kg usable hydrogen), and power conversion and conditioning equipment to produce stable 208 VAC power. These subsystems were assembled within a standard 20-foot ISO shipping container. Figure 2 shows a picture of the containerized MarFC system.

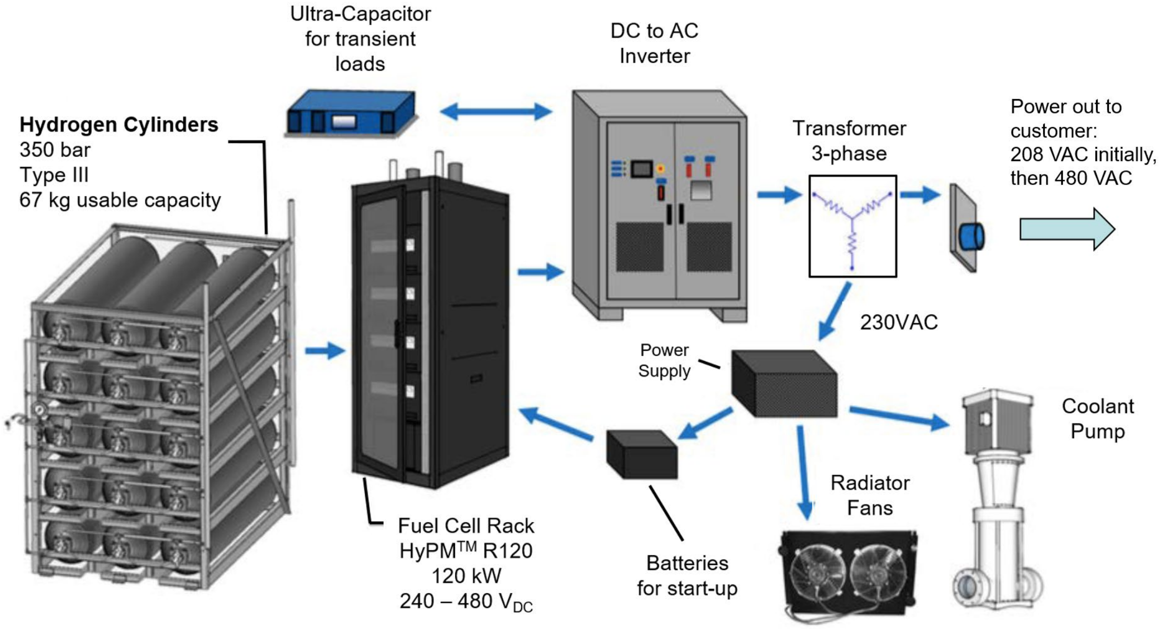


**Figure 1. Schematic diagram of the MarFC components and systems.**

**Figure 2. The 100-kW MarFC unit, with integrated hydrogen storage, PEM fuel cell and power conditioning equipment. The containerized MarFC is 19'10.5" long, 8.0' wide, 8'6" tall, and weighs approximately 25,000 lbs.**

Key early dates in the project include:

5/2014: Design review meeting at Cummins/Hydrogenics to finalize the design.

9/2014: The USCG issues the Design Basis Letter.

6/2015: Completion of Factory Acceptance Testing at Cummins/Hydrogenics.

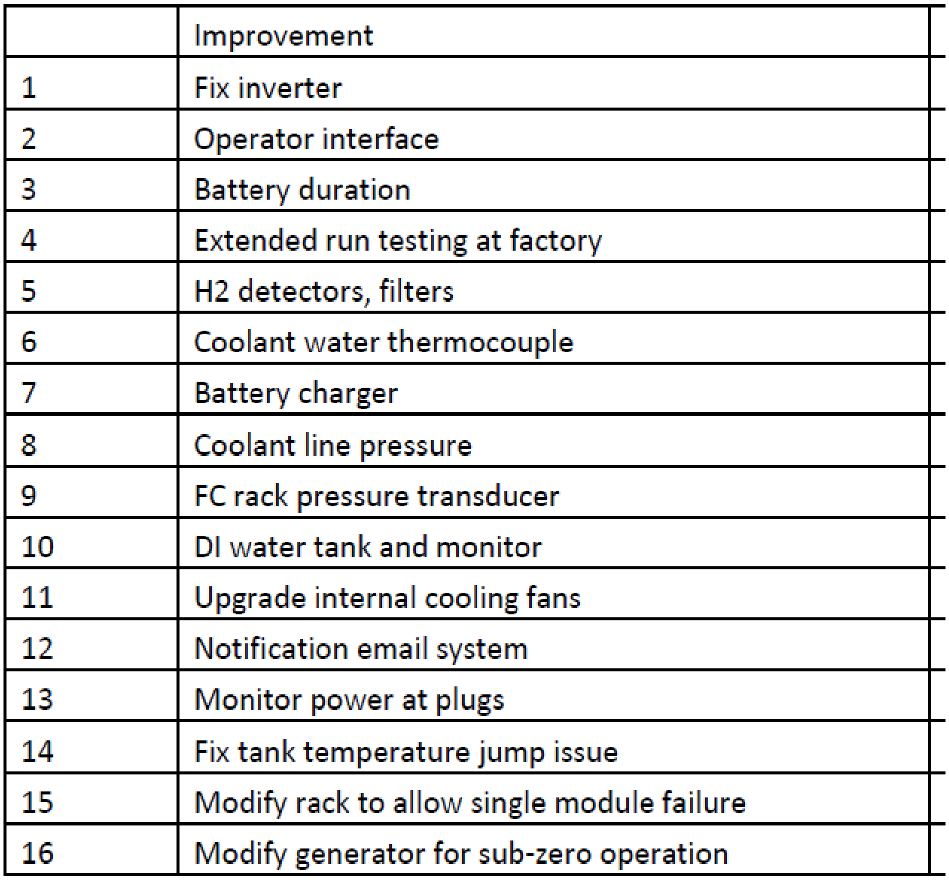
The first opportunity to validate the use of MarFC power in the marine environment was identified in Honolulu Harbor at the Young Brothers Ltd. wharf. At this facility, barges sail regularly to and from neighboring Hawaiian Islands and containerized diesel generators provide power for the refrigerated units (i.e., "reefers") while on the dock and on the barge during transport. Due to inherent efficiency advantages of fuel cells over diesel generators, switching to a hydrogen fuel-cell power generator to replace the incumbent diesel-based reefer technology promised significant emissions and cost savings.

The project began its first deployment over the period 8/2015 to 6/2016 hosted by Young Brothers Ltd. The deployment involved exclusively land-based dockside operation of the MarFC, as shown in Figure 3.

**Figure 3. The blue MarFC unit providing power for reefers at the Young Brothers Ltd. facility in Honolulu, HI.**

Since traditional (diesel-based) reefers operate on 208 VAC power, the power conversion equipment on the MarFC included a 208 VAC transformer.

During the deployment, feedback and data were collected to determine the electrical performance, as well as the environmental, energy, and cost savings from the MarFC unit. Sandia analyzed the operational, safety, and cost performance data to develop a business case for using hydrogen fuel cells at other commercial ports [1]. Deployment in Hawaii showed the unit needed greater reliability in the start-up sequence, as well as an improved interface to the end user, thereby presenting opportunities for repairing/upgrading the unit for deployment in another locale. All of the items needing attention are summarized in Figure 4. These items included internal heaters to allow the unit to operate in a future sub-freezing environment and upgrading the internal hydrogen detectors in the MarFC.



| | Improvement |
|---|---|
| 1 | Fix inverter |
| 2 | Operator interface |
| 3 | Battery duration |
| 4 | Extended run testing at factory |
| 5 | H2 detectors, filters |
| 6 | Coolant water thermocouple |
| 7 | Battery charger |
| 8 | Coolant line pressure |
| 9 | FC rack pressure transducer |
| 10 | DI water tank and monitor |
| 11 | Upgrade internal cooling fans |
| 12 | Notification email system |
| 13 | Monitor power at plugs |
| 14 | Fix tank temperature jump issue |
| 15 | Modify rack to allow single module failure |
| 16 | Modify generator for sub-zero operation |

**Figure 4. A summary of the MarFC items needing upgrade/repair after the first deployment with Young Brothers, Ltd., in Honolulu.**

With the identification of these items (Figure 4), this first phase of the project, from 2013 – 2017, came to an end, with a description of all the project activities given in the prior report [1]. This first phase of the project was led by Joe Pratt and Shuk Han Chan, both formerly of Sandia. Thereafter, the project has been led by Lennie Klebanoff of Sandia.

# 3. PROJECT ACTIVITY (2018 – 2023)

## 3.1. Fiscal Year 2018

In this year, actions were taken to rectify issues and upgrade/improve the MarFC in accordance with the list in Figure 4 and seek the next deployment site and partner with the improved MarFC unit.

Early in the year, Cummins/Hydrogenics completed its upgrade and repair of the MarFC unit, as well as testing of the unit in cold weather. The earlier deployment with Young Brothers Ltd. showed that the reliability of the MarFC conditioning electronics upon start-up needed to be improved. This problem was resolved. Working with ABB's maritime group based in Finland, Cummins/Hydrogenics modified the MarFC to include a proven ruggedized HESS-880 inverter solution, shown in Figure 5.

**Figure 5. Improved ABB Inverter.**

The complete solution included other electronic components including a 440 VAC to 230 VAC step-down transformer and filtering of the AC output. Feedback from Young Brothers operators indicated that the system display was inadequate, since the display did not convey the state of the system upon startup. This was resolved by installing a ruggedized system display shown in Figure 6, making it easy for the operator to ascertain the state of the MarFC, especially during start-up.

In anticipation of the MarFC being used in weather not as inviting as that found in Honolulu, system heaters and controls were added to allow the MarFC to operate in weather down to -25°C, as shown in Figure 7.

**Figure 6. Installation of a ruggedized system display, making it easy for the operator to ascertain the state of the MarFC, especially during start-up.**

**Figure 7. System heaters and controls that were installed to allow the MarFC to operate in weather down to -25°C in anticipation of a future deployment in cold weather.**

After completion of the repairs/upgrades, the unit was tested both indoors as well as outdoors in cold weather at the Cummins/Hydrogenics site in Mississauga, Ontario, Canada as shown in Figure 8.

**Figure 8. (L) Indoor testing of the MarFC unit at Cummins/Hydrogenics after system repair and upgrade; (R) outdoor testing of the MarFC unit in cold weather at the Cummins/Hydrogenics site in Mississauga, Ontario, Canada, December 2017.**

Different test data were logged during the outside test, including output power and temperatures of the fuel cell and inverter coolants and container interior. Example test data is shown in Figure 9. Pending identification of a suitable deployment site, the MarFC was then moved to a temperature-controlled storage facility nearby the Cummins/Hydrogenics facility.

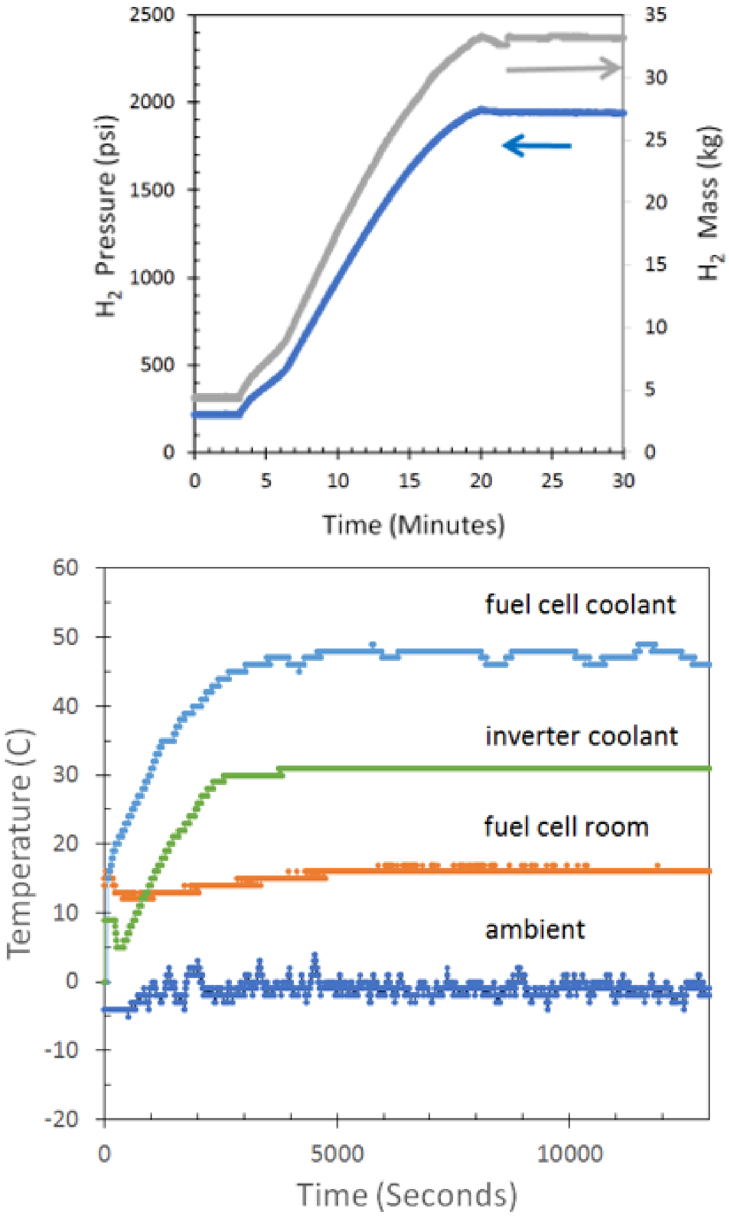


**Figure 9. Test data logged during the outside MarFC test. (Top) Hydrogen refueling rate data; (Bottom) MarFC system temperatures during operation.**

In seeking a potential deployment site, a number of factors must be considered so that the deployment satisfies the applicable regulatory conditions. A site may have its own specific insurance/indemnification requirements. In addition, a facility that involves hydrogen refueling or $H_2$ storage must satisfy National Fire Protection Association (NFPA) 2, the Hydrogen Technologies Code. NFPA 2 proscribes hydrogen system "setback distances" to lot lines, overhead power lines, distances to air intakes (HVAC, compressors), operable and inoperable wall openings, and distances to parked vehicles, ignition sources and the storage of other flammable gases.

Initially, the Port of Massachusetts (Massport) was identified as a possible next deployment location for the powering of reefers. Unfortunately, Massport and Sandia could not come to agreement on the legal and insurance terms and conditions. Subsequently, at the recommendation of Christine Houston, Manager of Sustainable Practices at the Port of Long Beach, the project contacted Captain Martin Curtin of Curtin Maritime (a tenant at the Port of Long Beach), with site visits on June 26, 2018, and July 19, 2018. Unfortunately, due to the long and narrow geometry of the Curtin Maritime lot, there was no location on the Curtin site that could satisfy the required NFPA 2 setback distances.

Summarizing the FY2018 work, the prior deployment in Hawaii pointed to several ways the unit needed to be improved and items needing repair. These upgrades and repairs were implemented and tested, with the result being a unit that was more reliable and easier for the operators to use. Two deployment sites were identified for the next use of the MarFC unit, but were found to be unsuitable for legal/regulatory reasons.

## 3.2. Fiscal Year 2019

The Scripps Institution of Oceanography (SIO) expressed interest in using the unit to cold-iron the research vessel *Robert Gordon Sproul* when in port at the SIO Nimitz Marine Facility in San Diego CA. The location of the Nimitz Marine Facility is shown in Figure 10.

**Figure 10. Location of the SIO Nimitz Marine Facility within the greater San Diego Area.**

The *Sproul* requires ~50 kW of shore power during the day, with a reduced ~14 kW of shore power at night, making it a good fit for the MarFC capabilities. Sandia (Klebanoff) and Cummins/Hydrogenics (Sookhoo) visited SIO to inspect the prospective space. The final legal and insurance discussions were completed between Sandia Legal and SIO (University of California, San Diego). These documents included a UCSD Waiver of Liability and Assumption of Risk Agreement, an Access Agreement for the Scripps Pier, and Sandia Certificate of Liability Insurance. These agreements cleared the path for the MarFC unit to be deployed at SIO.

Figure 11 shows that the Nimitz Marine Facility at SIO satisfied the space requirements to host the MarFC while also satisfying the NFPA 2 setback requirements for the storage and use of compressed hydrogen.

**Figure 11. (Top): the SIO research vessel *Robert Gordon Sproul*, in port at the Nimitz Marine Facility of the SIO, San Diego, California. The blue box notionally indicates the contemplated deployment and location of the MarFC; (Bottom), distances from the MarFC unit to nearby buildings (red) and lot lines (yellow), showing compliance with NFPA 2.**

The SIO vessel *Robert Gordon Sproul* requires 480 VAC power, whereas the MarFC unit was designed for 208 VAC power as required by reefers. The vast majority of shoreside power needs involve 480 VAC. As a check of the ability of the MarFC to meet the shore power needs, SIO Marine Superintendent Zoltan Kelety provided the international standard for high-voltage shore connectors, IEC/IEEE 80005-1:2019 as a check for MarFC compatibility with industry standards Comparison with the standard indicated the MarFC could indeed provide the needed power. Thus, to satisfy the immediate needs of the *Sproul*, as well as likely future deployment needs, plans were made to replace the MarFC 208 VAC transformer with a 480 VAC transformer. In addition, a new junction box (connecting the MarFC to the *Sproul* shore power cable) was designed to ensure compatibility with the existing shore-power electrical cabling for the research vessel.

In order to provide shore power for the *Sproul*, the MarFC unit had to be converted from 208 VAC to 480 VAC operation. This included replacing the existing power transformer with a new transformer of 480 VAC three phase (120 kVA) operation, changing the user power connector interface on the MarFC unit to a new connection terminal, and defining support equipment such as coolant pumps to operate with the new voltage.

The 480 VAC transformer was ordered from ABB, and it arrived and was installed at the Cummins/Hydrogenics facility in Mississauga, Ontario, Canada, as shown in Figure 12.

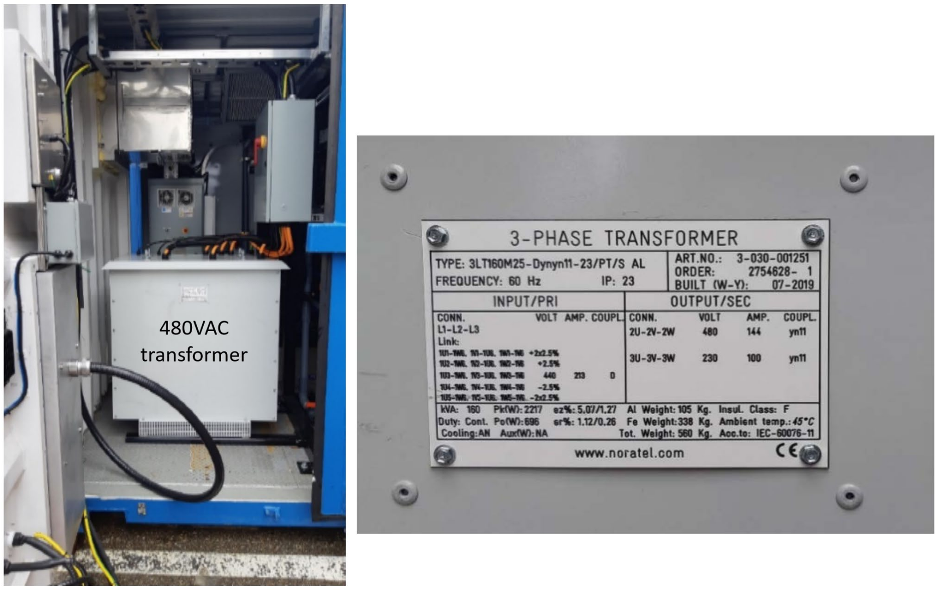


**Figure 12. New transformer installed, with associated nameplate expanded.**

The old 208 VAC transformer was placed in storage should the need for AC power at that voltage arise in the future. Beyond the installation of the transformer, the MarFC unit was modified to incorporate a new junction box permitting connection to the existing electrical cabling for the R/V *Robert Gordon Sproul.* This junction box work was performed with the electric connections recessed, preserving the MarFC qualification as a "shipping container," while at the same time conforming to the SIO request for three-wire connection to the R/V *Robert Gordon Sproul*. The new junction box is shown in Figure 13. Logos for the unit were also updated to include SIO as a project participant.

Figure 13. New recessed connector panel/box mounted on the MarFC unit for use at SIO.

After installation of the new transformer, the unit was tested for a two-week period in which power output was stopped and started, and the unit was run for endurance testing. Specifically, the unit was tested for 480 VAC 3-phase operation, voltage stability, assessing for voltage spikes, stability with repeated starting and stopping, output power endurance for 10 hours, effectiveness of the internal heaters, and assessing performance with variable loads. Figure 14 shows a picture of the unit during testing.

Figure 14. The 100-kW MarFC unit in place for electrical testing at Hydrogenics in FY 2019.

An example of the test data monitoring electrical bus voltage and power during “on-off” power cycling is shown in Figure 15. The unit passed this test phase, with the MarFC meeting all performance requirements.

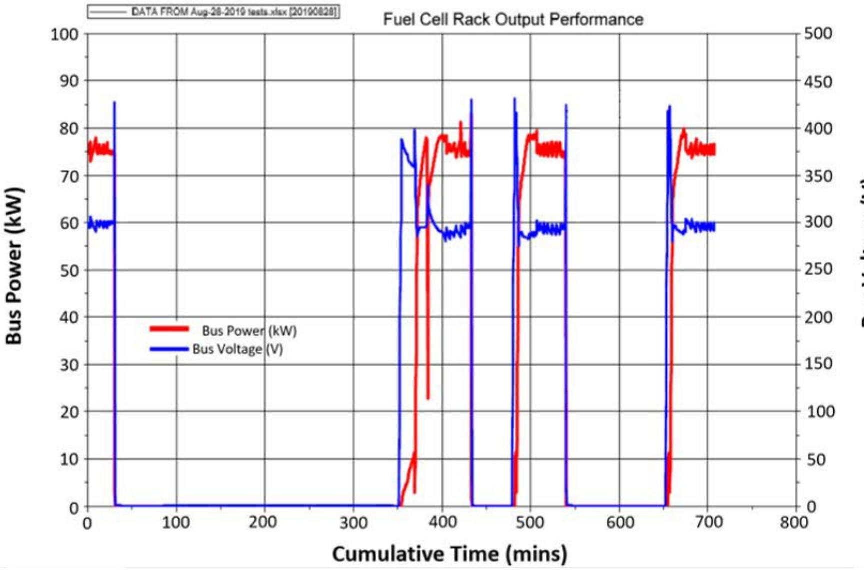


**Figure 15. Example test data from the 2-week tests of the modified MarFC unit, prior to shipment to SIO.**

Summarizing the FY2019 work, the team engaged with SIO to use the MarFC to power the research vessel R/V *Robert Gordon Sproul* while in port at the Nimitz Marine Facility in San Diego. The site was determined to be a good use of the unit and compatible with the applicable hydrogen regulations and legal requirements. The project secured legal and insurance agreements between Sandia and University of California, San Diego (UCSD) for the deployment of the MarFC at SIO. The MarFC unit was upgraded (transformer, connections, internal heaters) to provide 480 VAC operation, as required by the R/V *Robert Gordon Sproul*, and to provide the proper electrical interface box. Extensive start-stop and endurance performance testing was conducted of the MarFC electrical upgrades in preparation for the SIO deployment.

## 3.3. Fiscal Year 2020

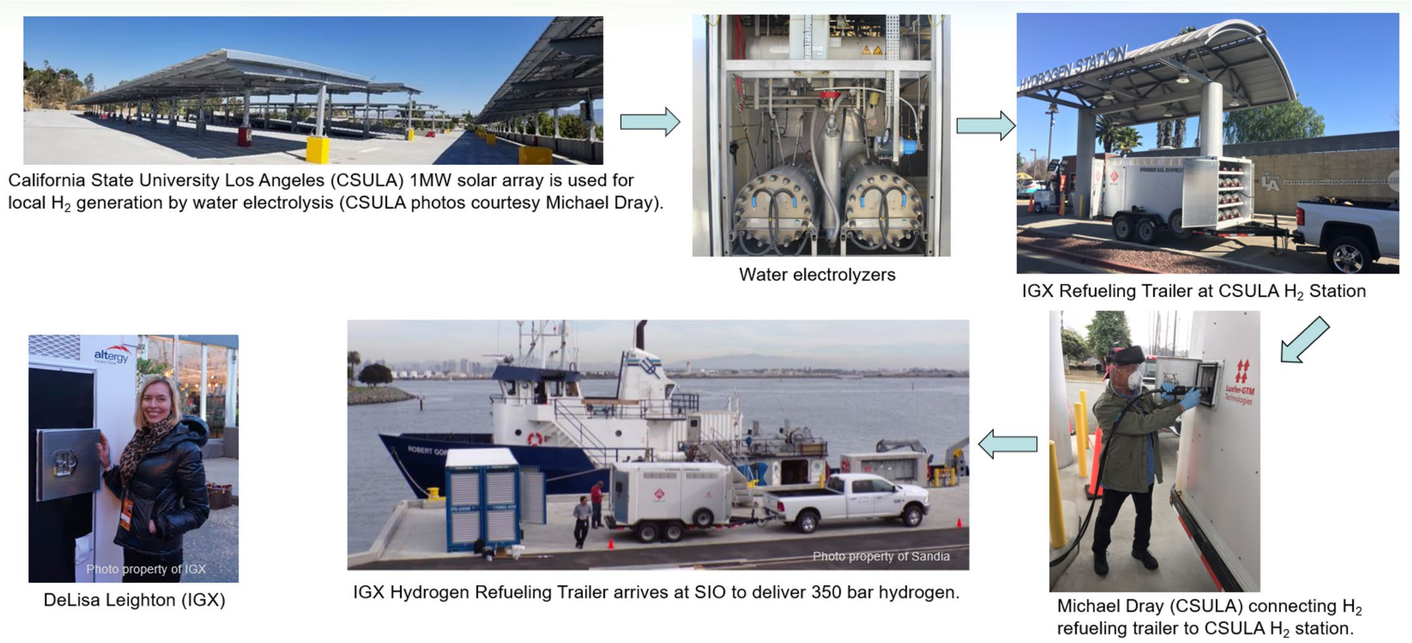
After testing, the unit was loaded onto a flatbed truck for shipment from Mississauga, Ontario, Canada to San Diego, as shown in Figure 16.

In order to have continuous support of the unit, weekly checking, and rapid response in the event of MarFC system problems, Sandia purchased a service agreement with Cummins/Hydrogenics to commence when the unit arrived at SIO.

**Figure 16. The MarFC unit being forklifted onto a flatbed truck for transport from the Cummins/Hydrogenics facility to San Diego, CA USA.**

To support the MarFC operation at SIO, Sandia contacted several hydrogen fuel suppliers to provide quotes for hydrogen fueling. IGX Group was selected to provide refueling from a GTM1500-450 450-bar-rated trailer that was well-suited for the MarFC unit, so long as it was not filled to higher than 350 bar pressure. The IGX Group fueling contract was established with fueling arranged to commence in November 2019 when the unit had been successfully delivered to SIO and has passed a post-delivery checkout. The contract with IGX was developed as a monthly service contract, assuming 3 refueling deliveries of hydrogen per week, with 43 kg of hydrogen per delivery. Over the course of one month, this comes to 516 kg total hydrogen delivered. The cost of the hydrogen per kilogram, pulling together a base gas cost/kg, a delivery and filling fee, and equipment rental fee (to guarantee availability of the refueling trailer) came to $42.44/kg. This cost is higher than one would pay at a hydrogen station (~ $15/kg at the time) because the hydrogen is being delivered, which incurs several costs (payment for driver, transportation costs, equipment rental).

The source of the hydrogen deserves special note. The IGX trailers were filled with hydrogen from the California State University Los Angeles (CSULA) hydrogen station, located ~ 120 miles from the Nimitz Marine Facility. The station provides 100% renewable hydrogen, produced by water electrolysis using solar power. The hydrogen produced is then compressed to 450 bar for onsite storage. A very important feature of the CSULA station is that it has a H35 hydrogen dispenser, providing hydrogen at 350 bar. This allowed the IGX trailer to be filled to 350 bar, enabling safe fueling of the 350-bar MarFC unit without the risk of over-pressurization. IGX then delivers the high-pressure renewable hydrogen to the Nimitz Marine Facility. Figure 17 shows the “process flow” of the operation.



California State University Los Angeles (CSULA) 1MW solar array is used for local $H_2$ generation by water electrolysis (CSULA photos courtesy Michael Dray).

Water electrolyzers

IGX Refueling Trailer at CSULA $H_2$ Station

Michael Dray (CSULA) connecting $H_2$ refueling trailer to CSULA $H_2$ station.

IGX Hydrogen Refueling Trailer arrives at SIO to deliver 350 bar hydrogen.

DeLisa Leighton (IGX)

**Figure 17. Process flow for supplying renewable hydrogen to the MarFC at SIO. Proceeding clockwise from the upper left, renewable hydrogen is sourced at the CSULA hydrogen station; the station employs water electrolyzers to produce hydrogen; and IGX trailer being filled at the CSULA hydrogen dispenser; Michael Dray (CSULA) connecting the refueling trailer to the station dispenser; arrival of the IGX refueling trailer at SIO; IGX employee DeLisa Leighton who arranged the fueling contract.**

The MarFC unit arrived at SIO on 11/11/19 and was placed next to the R/V *Robert Gordon Sproul*, as shown in Figure 18.

**Figure 18. Placement of the MarFC near the *R/V Robert Gordon Sproul* at the SIO Nimitz Marine Facility, San Diego CA.**

Initial inspection of the MarFC revealed that the unit arrived with broken PVC piping on the fuel-cell coolant recirculation system. Presumably, this occurred during customs inspection of the unit upon arrival in the United States, although the real cause remains unknown. On 12/1/19 a service team (Dave Haywood, Max Muller) arrived from Cummins/Hydrogenics. The old glycol coolant fluid was drained, the broken piping was removed, new piping was installed, and new glycol fluid added. Figure 19 documents some of these repair activities. The piping adhesive was allowed to dry for a couple of days before attempted refueling and use of the unit.

**Figure 19. (L) Dave Haywood drains old coolant from the MarFC recirculation system; (M) Max Muller removes broken PVC piping from the MarFC coolant system; (R) the new gray PVC coolant pipe successfully installed.**

These repairs allowed the first scheduled refueling of the MarFC unit by IGX on 12/2/19. The MarFC unit was shipped with minimal hydrogen pressure (~ 7 bar) for transport safety reasons. The MarFC was "cascade-fueled" to 350 bar by the IGX delivery trailer (operated by IGX employee Craig Van Pelt). Figure 20 documents the onsite refueling activity at SIO.

**Figure 20. Clockwise from upper left: IGX $H_2$ refueling trailer arrives at SIO on 12/2/19; Craig Van Pelt (IGX) prepares the trailer for cascade filling; successful connection of the trailer $H_2$ hose (green hose) and copper grounding connection to the MarFC; the temperature of the MarFC hydrogen tanks is monitored during refueling to ensure compression-heating does not heat the tanks too much.**

With the MarFC unit repaired, successfully fueled and proven operational, a series of educational seminars were presented to the SIO staff who either work pierside at the Nimitz Marine Facility, or work on the *Sproul* itself. The educational seminars were conducted on the morning of 12/3/19, with a tour of the MarFC hardware and example refueling conducted in the afternoon. Figure 21 presents photos from the morning session and afternoon trainings.

On the Physical and Combustion Properties of Hydrogen Compared to Natural Gas

Lennie Klebanoff
Sandia National Laboratories
Livermore, CA 94551

Scripps Institution of Oceanography
San Diego, CA
December 3, 2019

**Figure 21. The training of SIO personnel on 12/3/19. Proceeding clockwise from the upper left, Scripps personnel gathered together for the training; cover page of the presentation given by Lennie Klebanoff (Sandia) on the "Physical and Combustion Properties of Hydrogen Compared to Natural Gas;" Max Muller (Hydrogenics Cummins) describes the MarFC layout; in the afternoon, outside on the pier, Max Muller gives a tour of the MarFC systems, including hydrogen storage and fuel-cell power systems; Max Muller describes the fuel-cell power rack to James McManus of SIO; Craig Van Pelt of IGX describes the $H_2$ fueling procedures using the IGX refueling trailer.**

The morning session began with a presentation by PI Klebanoff on the Physical and Combustion properties of hydrogen compared to natural gas [7]. The comparison was made to natural gas because most people have some familiarity with natural gas use in their homes for cooking or water heating. The physical properties discussed included hydrogen liquid density, heat of vaporization, boiling point and lower heating value. In addition, the traditional means of storing hydrogen (high-pressure tanks, cryogenic tanks) were described. Finally, the phenomena of hydrogen embrittlement and hydrogen permeation were described in the context of the practical use of hydrogen plumbing hardware. The combustion characteristics described were definitions of hydrogen combustion terms (i.e., fire versus deflagration versus explosion), the flammability and explosive ranges, ignition energy, deflagration to detonation transitions, the nature of hydrogen fires (burn time, thermal radiation). At the end of this training, the SIO staff had a good understanding of the physical and combustion properties of hydrogen that underly safe hydrogen use practices.

In the afternoon, Max Muller (Cummins/Hydrogenics) introduced the SIO staff to the MarFC hardware (both $H_2$ storage power systems), as shown in Figure 21. The procedures for turning the MarFC unit on and off, and how to monitor it were reviewed. Finally, the refueling procedures were described by Craig Van Pelt from IGX using the IGX refueling trailer as a demonstration, as shown in Figure 21.

A couple of weeks later, on 12/19/2019, the first attempt was made to power the R/V *Robert Gordon Sproul* with the MarFC. This test was conducted with Sandia, Cummins/Hydrogenics and SIO staff collaborating on the hookup and monitoring of vessel systems. The power testing began with the *Sproul* mechanical systems, as shown in Figure 22. During this testing, all computer systems on the vessel and in the scientific bays were turned off as a protective measure.

**Figure 22. The initial powering of the R/V *Robert Gordon Sproul* mechanical systems with the MarFC on 12/19/19. Proceeding clockwise from the upper left, Captain Chris Welton (left) and James McManus connect the 480 VAC 3-phase vessel cable to the MarFC via the new junction box; Ernesto Bayer turns on a deck pump; Ernesto Bayer turns on the fire pump systems; and James McManus tests the operation of a deck crane while operating on MarFC power.**

The *Sproul* mechanical systems were turned on sequentially with the power consumption monitored at the MarFC user interface. The vessel lights, air conditioning and one ventilation fan were turned on first, drawing ~ 22 kW from the MarFC unit. Then the hydraulic systems and a second ventilation fan were turned on, bringing the accumulated power consumption to ~ 36 kW. After a suitable period of time (~ 15 minutes), the fire and steering pumps were turned on, bringing the power draw in the MarFC to ~ 50 kW. Finally, a deck crane was operated, bringing the total mechanical system power load to ~ 65 kW. The system was left at this power load for ~ 15 minutes, and the systems powered down. During the entire mechanical load test, the largest observed transient load was ~ 83 kW. Summarizing, all mechanical system power loads were comfortably handled by the MarFC.

The next systems that were tested were the powering of the *Sproul* computer systems, both navigational and in the science bays, with monitoring of these systems by Capt. Welton, as shown in Figure 23.

**Figure 23. (L) Capt. Chris Welton monitoring the *Sproul* computer systems during the initial powering of computer equipment with the MarFC; (R) Capt. Welton monitoring uninterruptable power supplies (UPS) in the science bay of the R/V *Robert Gordon Sproul*.**

Attempted MarFC powering of the *Sproul* computer and science systems was not successful. Monitoring of these systems showed that the battery-based UPS systems in some cases cycled on and off. In other cases, the UPS systems turned on, and their batteries quickly drained. Some damage to *Sproul* systems occurred, including damage to two power supplies. Recovery involved a significant amount of unplanned (and unbudgeted) labor by SIO IT staff to get the ship's systems working in time for the next science mission. It speaks to SIO as a project partner that they covered the cost of this recovery.

When these problems occurred, the MarFC unit was powered down and disconnected from the vessel. There then followed detailed discussions between Cummins/Hydrogenics and SIO electrical technicians responsible for the *Sproul*. SIO provided an electrical wiring diagram of the vessel to aid the discussions. Cummins/Hydrogenics then engaged in discussions with their power electronics subcontractor ABB. The consensus was that the issues could be traced to a MarFC-vessel interface grounding issue.

During the original site assessment, the existing grid pier docking power station was reviewed and determine to be a "Phase-to-Phase" voltage system. The MarFC was reconfigured to supply the same voltage and frequency as the grid pier docking power station. At this stage it was assumed all equipment on the *Sproul* was Phase-to-Phase powered. However, after the failed attempt to power the *Sproul* computer systems, it was discovered that the computer systems of the *Sproul* were in fact "Phase-to-Neutral." The equipment which were Phase-to-Neutral did not function properly because the power being supplied by the MarFC was Phase-to-Phase.

Explaining the situation in more detail, the MarFC unit was designed to generate three 220 VAC phases oscillating in time, such that at any given moment, there is 480 volts between any two phases. For the mechanical systems, this type of power is acceptable. However, the computer and science systems onboard the *Sproul* are designed to be powered by 120 VAC phase-to-neutral power. This requires a well-defined neutral from the power system, which the MarFC did not provide as part of its design.

To correct this issue, the Cummins/Hydrogenics team reviewed the existing grid power station and determined the power transformer was grounded. The MarFC did not have a grounded power transformer. A grounded cable was installed to ground the MarFC power transformer to provide the "neutral" needed by the *Sproul* computer systems. Unfortunately, we were not able to retest with the MarFC with the *Sproul* to confirm the fix worked, as the Covid-19 pandemic occurred just before the testing could be completed. In March of 2020, the Covid-19 pandemic then produced a pause in the on-site activities for the remainder of the FY2020 year.

Summarizing the work in FY 2020, the MarFC unit was shipped from Mississauga, Ontario, Canada to San Diego, CA. A fueling contract with IGX was established to support the MarFC unit at SIO, with renewable hydrogen provided by the CSULA hydrogen station. Inspection of the unit after shipping revealed damage had been sustained in transit to SIO, namely a broken PVC pipe in the fuel-cell coolant recirculation system. The damaged pipe was replaced by Cummins/Hydrogenics staff. The project team provided training to SIO staff on the physical and combustion properties of hydrogen, as well as classroom overview of the MarFC system followed by a tour of the unit itself. Hydrogen refueling procedures were described by IGX. The first fueling of the unit at the SIO pier was successfully completed by IGX. The first powering of a vessel with fuel-cell shore power was conducted with the R/V *Robert Gordon Sproul*. While the mechanical systems (lights, AC, ventilation, hydraulics, pumps, and cranes) were powered without incident, problems arose when powering the computer systems. Analysis of the vessel electrical diagram and consultation with ABB indicated the problem lay with a MarFC-vessel interface issue, which could be remedied with a suitably placed grounding cable in the MarFC. All onsite operations were then suspended for the remaining about 8 months of FY 2020 by the Covid-19 pandemic.

## 3.4. Fiscal Year 2021

The COVID-19 pandemic produced a pause in project operations from March 2020 to April 2021. Part of this delay was due to SIO personnel being consumed with the high difficulty of operating international research vessels during a pandemic. During this time, the PI Klebanoff conducted phone calls in the interim with the project team to keep the team together. Several paperwork activities were conducted during the delay, including executing a “no-cost extension” of the maintenance contract with Cummins-Hydrogenics on 3/2021, and executing a new $H_2$ fueling contract with IGX that same month.

During the shutdown, the unit was moved from its original location (Fig. 11) to a new location as indicated in Figure 24.

**Figure 24. (L) Overhead view of the Scripps Nimitz Marine facility, showing the old and new locations of the MarFC unit indicated in red. (R) Photograph of the MarFC unit in its new location.**

SIO moves their ships on occasion from place to place on the wharf and pier in response to operational needs. As a result, SIO had to move the R/V *Robert Gordon Sproul* on the Pier. The ability of the MarFC to be simply forklifted to the new location demonstrates the portability of the MarFC, allowing shore-side power to be established at a new location with no added cost. Portability is a main attribute of the containerized MarFC system. The new location served the project even better than the original location because the MarFC had greater visibility to passing marine traffic (the MarFC was no longer hidden behind the *Sproul*), and the MarFC is further away from neighbors, reducing possible noise complaints.

When the unit was shut down in March of 2020 due to the California shelter in place order, the unit was left “as is,” thinking that the shelter in place order would be lifted in a couple of weeks. Thus, the long-term storage of the unit from March 2020 to April 2021 was under non-optimal conditions in a maritime environment. The first visit to the unit occurred on April 6, 2021, when inspection took place, maintenance was performed, and initial pierside power tests (with a resistive load bank) were conducted. Inspection of the unit showed that the MarFC passed this physical test in the maritime environment with only routine maintenance needed.

The inspection/repair team is shown in Figure 25.

**Figure 25. (L) The Inspection/Repair Team: (L-R) Luis Orosco, Al Reeves, Ed Paz and Jayant Arora (all from Cummins/Hydrogenics) and Lennie Klebanoff (Sandia); (R) Photo of the bleached-out operator display.**

Inspection of the unit revealed the following:

- All the major subsystems (fuel cells, balance-of-plant, power conditioning electronics, $H_2$ storage tanks) were in good physical condition.
- There were no hydrogen leaks detected from the hydrogen tanks or manifolds.
- The coolant was old and showed unacceptably high electrical conduction (~ 70 microsiemens).
- The systems batteries (that allow unit start up) needed to be recharged.
- The external display that allows a user to operate the unit was bleached out, presumably due to prolonged sun exposure (see Figure 25 (R)).

Maintenance/repair activities commenced on 4/21/2021 and shown in Figure 26.

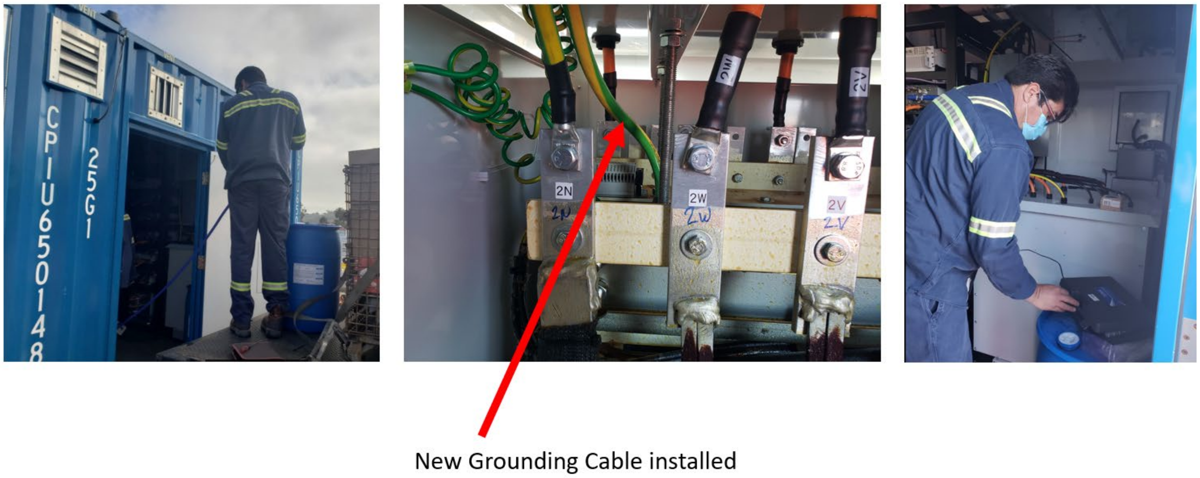


**Figure 26. (L) Ed Paz (Cummins/Hydrogenics) drains old coolant from the system and replaces it with new coolant; (M) the red arrow points out where the new grounding cable was installed; (R) Ed Paz checks the electrical function of the newly installed grounding cable.**

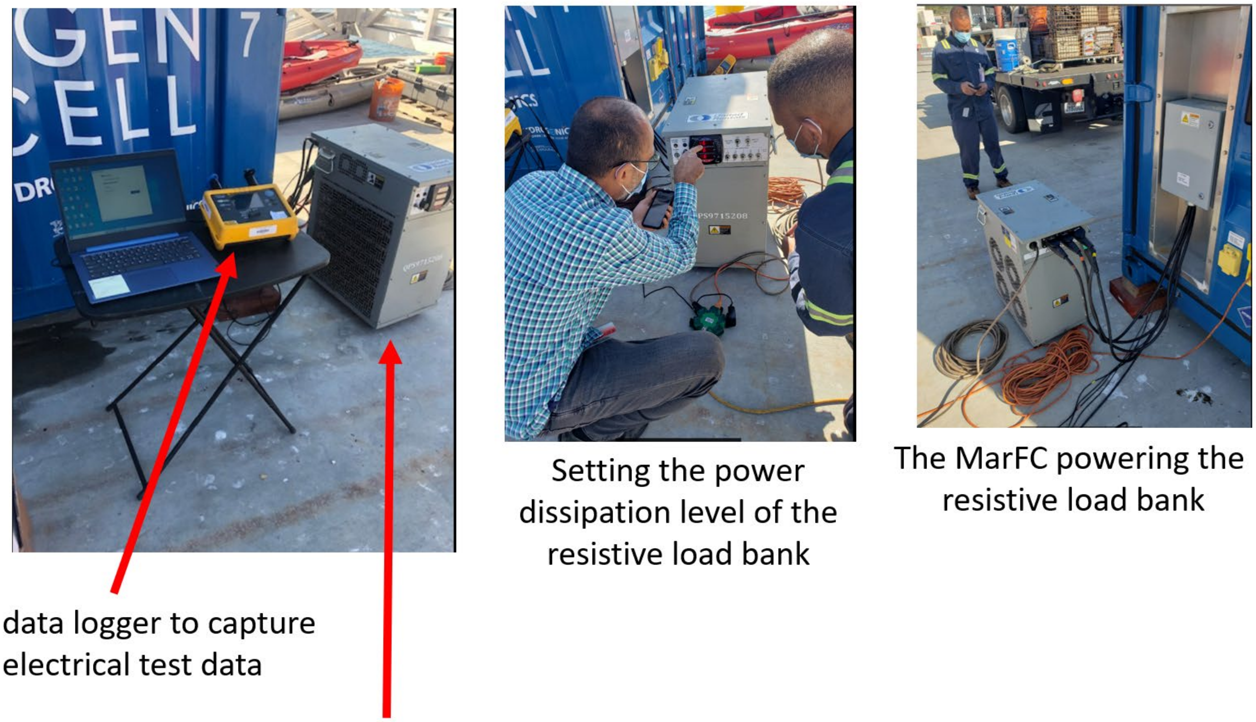
The team performed the following:

- Installed the transformer grounding cable, which hopefully will resolve the prior *Sproul* computer powering issues.
- Replaced the old coolant from the fuel-cell cooling loop, since the conductivity was too high, and also replaced a filter. Conductivity after the repair was at an acceptable 9 microsiemens.
- Recharged the system start-up batteries with on-site 110 V power.

A few items could not be immediately attended to. These included:

- The need to tune the power electronics and fuel cells for deployment.
- A Subscriber Identity Module (SIM) card needed to be installed to allow wireless communication between the MarFC unit and Cummins/Hydrogenics headquarters.
- The bleached-out computer screen was a long lead-time item that could not be immediately replaced.

An initial test of the repaired/upgraded unit commenced the next day, on April 22, 2021, as captured in Figure 27. The idea for this test was that although more upgrades needed to be performed on the unit before a final "Pierside Test" of the unit could be conducted before hookup to *Sproul*, an initial examination of system output after the year-long pause was necessary.



Setting the power dissipation level of the resistive load bank

The MarFC powering the resistive load bank

data logger to capture electrical test data

480 VAC 100 kW resistive load bank to test the 100 kW MarFC output and stability

**Figure 27. (L) A data logger was used to monitor MarFC electrical output in powering a 480 VAC 100 kW resistive load bank; (M) Jayant Arora (left) and Al Reeves (right) set the power dissipation (load) levels on the resistive load bank; (R) Al Reeves monitors the MarFC powering the resistive load bank.**

A 480 VAC 100 kW resistive load bank was used to test the level and stability of the MarFC power output as the load bank was stepped through relevant power dissipation levels. This initial overall test consisted of first powering up the MarFC unit with no external load, just the parasitic load of 5-10 kW. When this low-level of power output looked acceptable, the MarFC was used to power the external load (i.e. load bank) at various settings of the external load up to 50 kW, as captured in Figure 28.

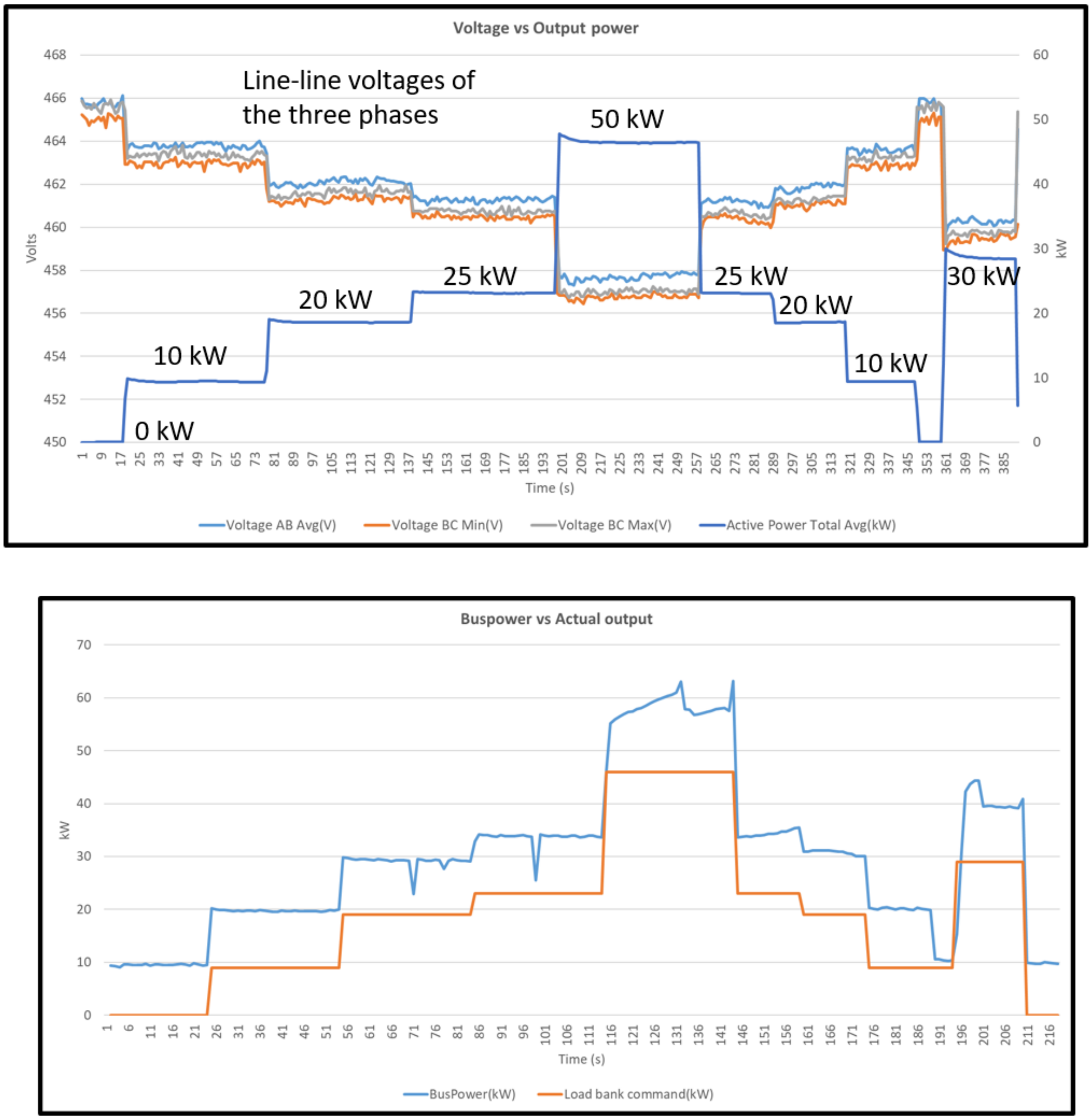


**Figure 28. (Top) Plot of measured line-line voltages of the three phases versus time, as well as the power output of the MarFC as a function of time as it is stepped through the various load settings up to 50 kW; (Bottom) Plot of bus power output versus time, along with the load bank dissipative load versus time.**

The overall conclusions from this initial testing were that the MarFC system was nominally working, but there were some instabilities and the fuel cells needed to be tuned. The unit has ultra-capacitors which need to be replaced due to age and usage. In addition, the unit inverter controls needed to be adjusted, since these factors can lead to the fuel-cell unit instability

Summarizing the FY2021 results, the Covid-19 pandemic caused the project to be paused until April 2021. The PI Klebanoff conducted phone calls in the interim with the project team to maintain progress on the project. During the pause, contract work (service, fueling) agreements were extended. SIO successfully moved the MarFC to a new SIO dock location to support the *Sproul*, thereby demonstrating the intrinsic portability of the MarFC power. Upon inspection in

April of 2021, the MarFC needed routine maintenance after a year of being turned off with no preparation. Maintenance was performed (coolant, batteries) and the unit was upgraded (grounding cable). The MarFC was turned on after the year pause, and initial test data on power levels and stability were collected.

## 3.5. Fiscal Year 2022

During this fiscal year, Cummins/Hydrogenics tuned the MarFC power electronics and fuel cells for use with the R/V *Robert Gordon Sproul*. In addition, 3 hydrogen detectors originally placed in the MarFC exceeded their operational life and were replaced. These replaced hydrogen detectors were also calibrated. In order for the MarFC to be remotely monitored, a wireless connection needed to be installed on the MarFC for communication with Cummins/Hydrogenics headquarters. To accomplish this, a SIM card was installed.

During the year of sitting idly on the SIO Pier due to the Covid-19 pandemic, the user interface display had become bleached out and unusable. This display was replaced with a new interface display to allow user control of the MarFC. In addition, several defective power supplies within the MarFC balance-of-plant systems were discovered and replaced. Continued inspection of the unit during these repair activities discovered a small hydrogen leak in the $H_2$ tank manifold. This leak was repaired.

Examination of the initial test data collected towards the end of FY2021 indicated that one of the four fuel-cell racks in the MarFC was experiencing problems. We needed to stay below 60 kW in total MarFC output power. The cause of the 60-kW power limit was two-fold. The first issue was the ultracapacitors installed to handle fast transient loads were degraded and needed to be replaced. As a result, if the unit was operating above 60 kW and a transient needed to be handled, there would be a power instability The second issue was that degradation was seen in the overall fuel-cell performance. The source of the degradation is unknown, but perforation or contamination of the PEM membranes within the modules is suspected.

Remedying these problems involved a cost beyond the resources of the project. Cummins/Hydrogenics thus recommended limiting further use of the MarFC to 60 kW or less. Consultations with Capt. Chris Welton (SIO) indicated that 60 kW was sufficient for providing shore power to the *Sproul*. However, due to the difficulties encountered during the last time the unit powered the *Sproul* computer systems, all parties in the project team agreed that there should be an extensive Pierside Test of the unit to not only test the grounding cable installation which was thought to solve the *Sproul* computer powering problem, but also to test all the upgrades and repairs that had been made in the past year. The Pierside Test was therefore limited to 60 kW total MarFC output power, and was formulated by Sandia and Cummins/Hydrogenics and approved by SIO. It was conducted in October and November of 2021.

Testing consisted of:

- Ramp the MarFC unit to 60 kW net output in 20 kW steps, then step back down.
- Ramp to maximum 60 kW load in one step, then step back down.
- Conduct first stability check, varying output between 0 and 60 kW.

- Conduct Endurance Test, running the MarFC for 4 hours at 60 kW.
- Conduct second stability check (after the Endurance Test), varying the output between 0 kW and 60 kW.

Example data from the tests are shown in Figure 29.

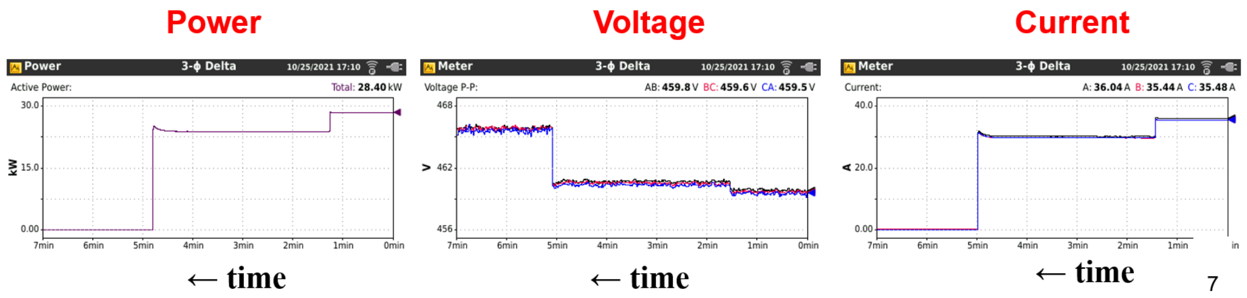


**Figure 29. Measurements of Power, Voltage and Current as a function of time during testing of the MarFC unit.**

Overall, the unit achieved 60 kW output, and could execute power steps of order 20 kW or less. The next testing involved more and larger power steps (both up and down in power), performing endurance testing (hours) and testing the unit again after the endurance test. The data from this further testing is shown in Figure 30.

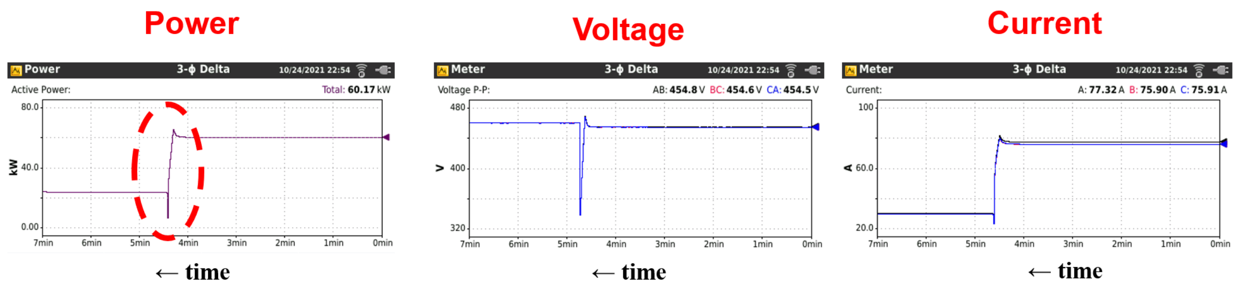


**Figure 30. Measurements of Power, Voltage and Current as a function of time during further testing of the MarFC unit. The dashed red circle indicates the occurrence of a dip in power seen during the testing.**

It is clear from Figure 30 that when decreasing the power from ~ 60 kW to ~20 kW, noticeable momentary "dips" in output power, voltage and current were detected (see the dashed red circle in Figure 30). This dip was attributed to the "battery bank" (ultracapacitor), used for instantaneous power changes, being too old (8 years). The testing revealed multiple momentary "dips" in output power/voltage/current for step changes of > 20 kW (both stepping up and down). The unit successfully passed the endurance test, operating at a plateau of 60 kW for 4 hours without issue.

Resolving the battery/dip issues required resources beyond those available to the project. As a result, the decision was made not to conduct the full (months) deployment with the R/V *Robert*

*Gordon Sproul*, because the effect of the voltage and power dips on the *Sproul* mechanical and electrical systems were unknown.

However, the project team (including SIO) agreed that the unit could safely be connected to the *Sproul* for a few hours in order to determine if the computer issues seen during the initial *Sproul* powering was resolved by the installed grounding cable (see Figure 26). In March of 2022, the project team formulated a "*Sproul* Hookup Test Plan" for SIO to review, which was approved. The Hookup to the *Sproul* was planned for June 2022, with deployment at SIO to end after the *Sproul* powering test was completed. That *Sproul* Hookup Test consisted of proving that computer systems on the *Sproul* could be powered via the MarFC. To protect *Sproul* computer systems, the PI Klebanoff would supply his own personal computers for the test. The Plan consisted of the following:

### Agreed-to Sproul Hookup Test Plan

1. Make sure the MarFC shipping container is still electrically grounded via external cable to the shore-side power ground, but NOT electrically connected to the vessel yet.
2. Turn on MarFC (with no external load) and ensure it is nominally operational.
    a. Check the user interface (screen) to see if the unit is properly powering the "balance-of-plant" load, which should be about 10 kW. Make sure the data logging equipment is operating correctly.
3. Turn off MarFC.
4. Secure (unplug or switch off) all electrical systems on the *Sproul* to ensure that when the fuel-cell unit is connected to the vessel and switched on, no vessel load or sensitive load is being powered.
    a. Note: Scripps technical staff will define what "securing" means in their eyes, to ensure safety for their systems. This "securing" procedure is TBD. Also, Scripps will identify in advance what systems cannot be unplugged and their expected power level so we understand what the initial "plug in" power level is expected to be.
5. Make electrical connection from MarFC to the vessel's electrical grid using the *Sproul* power cable, with the data logging power/voltage/current monitoring in place.
6. Turn on MarFC
    a. Check 110 VAC on the vessel to see if it is present and stable using a digital voltmeter. Test the 110 VAC on the vessel using a small plug-in lamp or power tool, just to put a small load on the circuit.
        i. If OK, connect the Cummins/Hydrogenics Surrogate UPS to the vessel 110 VAC, which is a Cyber Power 1500VA 1500W UPS system, purchased by Cummins/Hydrogenics, and duplicates the Scripps UPS on the vessel (which had problems before).
    b. If the Cummins/Hydrogenics UPS is OK (UPS does not trip), connect Lennie's personal computers (a laptop computer, then a desk computer) to the Cummins/Hydrogenics UPS. See if there are any issues with powering computers.
    c. If OK, plug in the *Sproul* UPS (with the *Sproul* computers not connected to the UPS) to the bus line/110 VAC. See if the *Sproul* UPS trips off like last time.

    d. If OK (*Sproul* UPS does not trip), plug in Lennie's personal computers (a laptop computer, then a desktop computer) to the *Sproul* UPS and assess. Note the load drawn and power stability.

7. If all is OK, terminate the test by shutting down Lennie's computers, turning off the MarFC and electrically disconnecting the MarFC from the vessel.
8. Test Complete.

About the time of the formulation of this test plan (March 2022), the R/V *Robert Gordon Sproul* entered "shipyard drydock" for repairs and upgrades, making it unavailable for testing of the MarFC. On May 17 of 2022, we were informed by Bruce Appelgate of SIO that due to supply chain problems and labor issues, *Sproul's* shipyard period was seriously behind schedule. As a result, SIO had to defer many high-priority seagoing science projects, rescheduling them into the periods in the summer and fall when they had planned to have some free time to perform the MarFC-*Sproul* Hookup Test.

The "testing environment" for SIO changed considerably with the supply chain issues and long lead times to effect repairs, making testing the MarFC very risky for SIO. Although SIO did not think anything would go wrong with the *Sproul* systems upon testing the MarFC again, if something did go wrong, SIO would not have the time, money, or people to recover in time to carry out their science missions. Overall, the work situation had changed dramatically for SIO, for the remainder of FY2022 and for FY2023 as well. Before Covid-19, *Sproul* had much more availability for testing and SIO had the bandwidth to support projects like this. Complicating the schedule of the *Sproul*, in 2021 one of the other West Coast research vessels (R/V *Oceanus* operated by Oregon State University) was retired from service, and many of that ship's programs shifted onto *Sproul* until OSU gets their new vessel in a year or two. For these reasons, for the foreseeable future, *Sproul* would not be available to test the MarFC.

After speaking with project team members SIO and Cummins/Hydrogenics, the team decided that it would not be possible to conduct the final test of the MarFC, and that it was time to remove it from the Scripps facility. Scripps had been an amazing deployment partner, but they could not reasonably continue given their situation.

On May 25, 2022, PI Klebanoff notified DOE and MARAD of the situation, and requested a meeting to discuss possible next steps for the MarFC unit. The meeting between DOE, MARAD, Cummins/Hydrogenics and Sandia took place on July 27, 2022. At that meeting, a number of possible "next steps" for the unit were discussed, but at the end, a consensus was reached that the unit, now 8 years old, was suffering from age-related problems, that would require significant investment to rectify. Also, because the fuel-cell technology within the unit was getting antiquated, any future testing of the existing unit would constitute field-testing old technology, which did not make sense. The decision was made to retire the existing MarFC unit from future field deployments. Removal was planned for FY 2023.

Summarizing, FY2022 was a year spent repairing, upgrading and testing the MarFC unit. The fuel-cell modules were tuned, hydrogen detectors that had exceeded their calibration/lifetime were replaced, a small hydrogen leak was found and corrected, the bleached-out user interface monitor was replaced and a remote monitoring (wireless) capability was added to the unit. Examination of the prior test data, and collection/analysis of subsequent test data indicated limitations of the output power to 60 kW, combined with risky spikes in power and voltage that could cause problems with the *Sproul* electrical systems. These age-related problems, combined with extended time for the *Sproul* spent in dry dock and the associated need to reschedule the vessel's high-priority science missions made it no longer possible to deploy the unit at SIO. The decision was made by DOE, MARAD and the project team to cease the deployment, remove the MarFC from SIO, and not pursue further deployment activities.

### 3.6. Fiscal Year 2023

On December 2, 2022, the MarFC unit was removed from the Scripps Nimitz Marine Facility, as shown in Figure 31. Austin Mattison, The Cummins/Hydrogenics Engineering Manager for the Fuel-cell Service Engineering Group, arranged and supervised the removal operation. The unit was shipped to Fridley, Minnesota. The Cummins/Hydrogenics plan for the unit is to first assess the condition of the MarFC subcomponents and then use the MarFC as a training system for technical employees new to hydrogen fuel-cell technology.

**Figure 31. (L) Craning the MarFC unit off the SIO Pier; (M) Craning the MarFC onto the flatbed truck and (R) The MarFC secured to the flatbed truck ready for shipment to Minnesota.**

# 4. SUMMARY OF PROJECT ACTIVITY (2018 – 2023)

This report summarizes activity in the MarFC Project during the period 2018 – 2023, with the project activities presented chronologically. The prior deployment in Hawaii [1] pointed to several ways the MarFC unit needed to be improved and items needing repair. These upgrades and repairs were implemented and tested in FY 2018, with the result being a unit that was more reliable and easier for the operators to use. In 2019, the team engaged SIO for use of the MarFC to power the research vessel R/V *Robert Gordon Sproul* while in port at the Nimitz Marine Facility in San Diego, CA. In FY 2020, the MarFC unit was shipped from Mississauga, Ontario, Canada to San Diego, CA. The first powering of a vessel with fuel-cell shore power was conducted with the R/V *Robert Gordon Sproul*. While the mechanical systems (lights, AC, ventilation, hydraulics, pumps and cranes) were powered without incident, problems arose when powering the computer systems. It turned out that the cranes, AC and ventilation all needed "phase-to-phase" power, which the MarFC was designed to provide. However, the computer and science systems were designed to be powered by "phase-to-neutral" power. This required a well-defined neutral from the power system, which the MarFC was not designed to provide. To correct this problem, a well-defined neutral was added in the form of an earth ground installed on the 480 VAC transformer within the MarFC.

All onsite operations were then suspended for the remaining about 8 months of FY 2020 by the Covid-19 pandemic, and up until April of FY 2021. FY2022 was a year devoted to repairing, upgrading and testing the MarFC unit. Examination of the prior test data, and collection/analysis of subsequent test data indicated limitations of the output power to 60 kW, combined with risky spikes in power and voltage that could cause problems with the *Sproul* electrical systems. These age-related problems, combined with extended time for the *Sproul* spent in dry dock and the associated need to reschedule the vessel's high-priority science missions made it no longer possible to deploy the unit at SIO. The decision was made by DOE, MARAD and the project team to cease the deployment, remove the MarFC from SIO, and not pursue further deployment activities using the existing MarFC unit. On December 2, 2022, the MarFC unit was removed from the Scripps Nimitz Marine Facility. The unit was shipped to Fridley, Minnesota where Cummins/Hydrogenics will use it to examine the condition of the MarFC components, and then use it to train new employees in hydrogen technology.

# 5. LESSONS LEARNED

Over the period FY 2018 to FY 2023, a number of lessons were learned about the field deployment of the MarFC in its mission to provide zero-emission portable power in the maritime context. These lessons are as follows:

## 5.1. 480 VAC is the Preferred Output Power

Originally, the MarFC was designed to provide 208 VAC power for reefer units used by Young Brothers Ltd. in Hawaii. However, when it came time to look for another deployment site, all of the possible deployment partners needed 480 VAC power, not 208 VAC power. This required the installation of a new transformer in the MarFC. Future containerized fuel-cell power systems should provide 480 VAC power if they are to be commercially viable.

## 5.2. Using Fuel Cells to Power Vessel Computer Systems is Not Straightforward, and the Detailed Electrical Architecture of the End Use Application Needs to be Fully Investigated in Advance

The first attempt at powering the R/V *Robert Gordon Sproul* was, to our knowledge, the first time in history a pierside fuel-cell power unit was ever used to power a moored vessel on the water. Although the mechanical systems (lights, AC, ventilation, hydraulics, pumps and cranes) were powered without incident, problems arose when powering the vessel's computer systems, resulting in the draining of battery-based UPS systems and some damage to vessel power supplies in the science bay. The problem was the MarFC was not providing a required "neutral" for the phase-to-neutral computer systems, which could be remedied with a suitably placed grounding cable within the MarFC unit. However, we were unable to test if this solution actually remedied the problem. Thus, we can conclude that powering vessel computer systems with a pierside fuel cell is not straightforward, and a detailed examination of the end-use electrical architecture is required. A successful powering of vessel computer components remains to be demonstrated.

## 5.3. The Need for Robust and Marinized Power Electronics

It should be noted that the MarFC power electronics were a customized solution for this project. More reliability testing and optimization of the controls is needed to further improve the system performance and stability for commercial maritime operation. It would be an improvement to marry the MarFC power electronics design to that being contemplated for heavy duty trucks.

## 5.4. The Cost of Hydrogen Remains High

In the original deployment of the unit with Young Brothers in Hawaii, prior to FY 2018, the hydrogen for the project was donated, free of charge, by the hydrogen station at Hickam Air Force Base. During the period covered by this report (FY 2018 to FY 2023), hydrogen was purchased on the open market. Thus, the first information associated with costs of mobile refueling was gathered during this second phase of the project. IGX fueling was developed as a monthly service contract, assuming 3 refueling deliveries of hydrogen per week, with 43 kg of hydrogen per delivery. Over 1 month, this comes to 516 kg total hydrogen delivered. The total cost of the hydrogen came to $42.44/kg. This cost is higher than one would pay at a hydrogen station (~ $15/kg at the time) because the hydrogen is being delivered, which incurs several costs (payment for driver, transportation costs, equipment rental). IGX deserves special recognition for being an exceptionally flexible service provider. During long periods when the unit was down for repair and upgrade, during the Covid-19 pandemic or when the MarFC could not be used when the *Sproul* was unavailable, IGX maintained the service contract while waiving the rental equipment fee. The cost of station hydrogen is even higher now than it was during the SIO deployment, and is currently ~ $23/kg.

The question arises if this $42.44/kg charge is expensive or not. It's a complicated question. Clearly, the delivered $H_2$ fuel is more expensive than delivered diesel fuel, to fuel an equivalent diesel generator, but a diesel generator is not zero-emissions like the MarFC. One operational benefit of the MarFC was clearly shown during the SIO deployment. The MarFC is portable. So if power needs to be supplied at a maritime location without power, the only zero-emission alternative would be establishing grid shoreside power, which can be enormously expensive and take time to install. There is no battery equivalent to the 100 kW MarFC currently available, and such a battery technology would in any event be much heavier and take up more space. So, the question ultimately comes down to if a commercial end-user is willing to pay ~ $42/kg for portable zero-emission power. The project was unable to answer that question.

### 5.5. Hydrogen Stations Should Maintain the Ability to Fuel at 350 Bar by Maintaining H-35 Dispensers at Their Locations

One of the enabling pieces of hydrogen infrastructure for this project was the presence of a H-35 (350-bar) hydrogen dispenser at the CSULA hydrogen station. The tanks on the MarFC are 350-bar tanks, which means they should be filled from 350-bar hydrogen on the IGX trailer. Although the IGX GTM1500-450 trailer is rated for a maximum pressure of 450 bar, for our project we needed it filled to a maximum pressure of 350 bar for safety. Thus, we needed a station that could fill to 350 bar a hydrogen trailer, which requires a H-35 dispenser which was present at the CSULA hydrogen station. If the station only had a H-70 dispenser, providing 700 bar hydrogen, the IGX trailer could not have been filled. Thus, it is important that select future hydrogen stations provide the ability to dispense both 350-bar hydrogen (using a H-35 dispenser) as well as 700-bar hydrogen (using a H-70 dispenser) to allow fueling of non-vehicle uses of hydrogen.

### 5.6. The Lifetime of Fuel-cell Power Units for 2014-era Technology is about 8 Years

The MarFC was a custom "one-off" proof of concept power system. It was successful in introducing the hydrogen fuel-cell technology to the marine application, and introducing key marine end users to hydrogen technology. There are key components within the unit which exceeded their projected life and, in some cases, had become obsolete. In particular, when the Covid-19 pandemic started, the project was abruptly paused and the unit was not properly conditioned for a prolong dormant period, which accelerated the degradation of some of the key sub-systems. Overall, after 8 years of service, accumulated age-related problems significantly degraded the MarFC performance to below acceptable levels.

# 6. COMPARISON WITH PROJECT AIMS

By comparing the original project aims with the project activity, we can assess to what extent the project aims were met.

## 6.1. Lowering the technology risk of future port fuel-cell deployments by providing performance data of hydrogen proton exchange membrane (PEM) fuel-cell technology in this environment.

The experience of deploying the MarFC with Young Brothers Ltd. clearly showed the improvements needed (in power conditioning electronics, user interface) in order to make the MarFC a more commercial-ready and operator-friendly product. The search for new deployment sites (Massport, Curtin Maritime) taught the important lesson that such units need to provide 480 VAC power to be commercially viable. The attempt to power the R/V *Robert Gordon Sproul* was the first time a fuel-cell-based shore power system was used to power a vessel. This experience taught invaluable lessons, that the powering of a vessel is not straightforward, and requires a detailed analysis of the vessel electrical system and how it mates to the power provided by the MarFC. Moving the MarFC from one end of the SIO pier to the other clearly demonstrated the power of MarFC portability, which is a primary driver for using the MarFC in locales where installation of grid-based shore power would be too costly and time consuming.

## 6.2. Lowering the investment risk by providing a validated economic assessment for this and future potential projects.

Since a long-term deployment of the MarFC was not achieved, the project provided less-than-hoped for data for an economic assessment. The initial deployment in Hawaii involved hydrogen donated by the hydrogen station at Hickam Air Force Base. While much appreciated by the project and enabling for the Hawaii deployment, this arrangement does not provide a realistic assessment of the commercial potential. The comparison to a commercial use of the MarFC was improved by moving the unit to SIO. There, the lowest cost hydrogen that could be obtained was $42.44/kg. However, the unit was not operated in a routine way at SIO, so the other operations and maintenance (O&M) costs for a routine commercial use could not be assessed. As a result, the project was unable to assess the economic prospects for the MarFC in the shore power marketplace.

## 6.3. Enabling easier permitting and acceptance of hydrogen fuel-cell technology in maritime applications by assisting the U.S. Coast Guard and the American Bureau of Shipping develop hydrogen fuel-cell codes and standards.

This objective was largely accomplished in the first phase of the project, where the USCG reviewed the MarFC technology and issued a Design Basis Letter.

## 6.4. Engaging potential adopters/end users of hydrogen fuel cells to enable more widespread acceptance of the technology.

This objective was accomplished by the first deployment with Young Brothers Ltd. in Hawaii, and the subsequent reporting of those results in various presentations. In the second phase from 2018 – 2023, the project engagement with Massport and Curtin Maritime, although not leading to deployment at these sites, spread the word about stationary fuel-cell shore power with these potential end users, and these potential end users became very familiar with hydrogen fuel-cell power as a result. The MarFC deployment at SIO gave SIO technical and administrative staff firsthand knowledge of hydrogen PEM fuel-cell technology. This experience had the effect of "taking the mystery out of" hydrogen fuel-cell technology, including the environmental benefits and the refueling methods. The comfort SIO obtained with the technology through the MarFC encouraged them to consider hydrogen PEM fuel cells as propulsion engines for their new research vessels [8, 9]. As a result, SIO proposed to the State of California the funding of a $H_2$ Hybrid Research vessel. The State responded with an award of $35M to build such a vessel.

# 7. NEXT STEPS FOR A POTENTIAL FOLLOW-ON PROJECT

Although much was learned from this project on bringing the MarFC through USCG approval, gathering initial performance data at 208 VAC, modifying the unit to 480 VAC operation and powering a vessel portside, even more could be learned with a well-targeted follow-on project that would advance further the use of zero-emission fuel-cell-based stationary power in a marine setting. Considerations for such a project are:

1. Demonstrate very early, using a small existing fuel-cell system that sensitive computer systems on a vessel could be successfully powered. This would be an important first step before building a new MarFC using current hydrogen fuel-cell technology.
2. Perform a market assessment for potential end users. The original MarFC was conceived and designed for its use powering reefer units at 208 VAC, and later retrofitted to provide the more prevalent 480 VAC power. However, the potential applications for portside stationary power go beyond reefer units. All potential applications for pierside fuel-cell power should be surveyed in order to better understand the design and performance requirements for a next-generation MarFC. For example, what power level should such a new 480 VAC MarFC system be designed to? How much hydrogen storage would be needed for a commercially attractive unit? This requires an up-to-date market assessment activity in a potential follow-on project.
3. Perform a technology gap assessment between the market needs identified above and what the fuel-cell technology is currently able to provide. For example, are different types of fuel cells (e.g., solid-oxide) more applicable than PEM technology for some shoreside applications?
4. Leverage recent innovations in fuel-cell technology. How could a next-generation MarFC leverage the dramatic reductions in fuel-cell footprint since the original project conception a decade ago? Would a "swap and replace" hydrogen storage system be better suited to the shore power application?
5. Design the next-generation MarFC to optimize alignment with other commercial fuel-cell applications. For example there is a lot of current interest in fuel-cell heavy duty trucks, which requires a fuel-cell power of ~ 300 kW. Can a fuel cell optimized for heavy duty trucks also be directly used for a next-generation MarFC? Such an alignment would dramatically promote the economic viability of a next-generation MarFC.
6. Improving reliability. The current MarFC had a number of reliability problems. Perhaps the first step in a new project would be to perform a forensic analysis of the components currently on the system to understand the reliability and performance shortcomings. Then, using this information, maximize the reliability (in a marine environment) of the fuel cells, power conditioning electronics, and the user interface displays.
7. Perform in-depth study of the electrical architectures of desirable end-use applications. A next generation MarFC would need to provide power that is compatible with the end-use application. This really needs to be studies in detail to avoid the "phase-to-neutral" problem we experienced with the *Sproul*.
8. Focus on cybersecurity. A next generation MarFC would have to have robust and high-bandwidth wireless communications capability, while at the same time guaranteeing secure communications and data storage. This topic was not addressed in the first MarFC

project but would be a very important contribution to making hydrogen fuel-cell power an attractive shoreside power option.

**Table 1. Presentations from the Project**

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| 2. L.E. Klebanoff, "Maritime Fuel Cell Generator Project," DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington DC (June 14, 2018). |
| 3. L.E. Klebanoff, "Maritime Fuel Cell Generator Project," DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, April 30, 2019. |
| 3. L.E. Klebanoff, "Development of a Containerized 100 kW Fuel Cell System for Maritime Applications," $H_2$@Ports DOE Workshop, San Francisco, CA, September 11, 2019. |
| 5. L.E. Klebanoff, "Maritime Fuel Cell Generator Project," DOE $H_2$ Program Annual Merit Review, Washington D.C., May 31, 2020. |
| 6. L.E. Klebanoff, *"Maritime Fuel Cell Generator Project,"* DOE $H_2$ Program Annual Merit Review, Washington D.C., June 10, 2021 (online meeting). |
| 7. L.E. Klebanoff, "Comparing $LH_2$ and LNG In the Context of $H_2$ Fuel Cell Vessels," United States Coast Guard Sector San Francisco, Yerba Buena Island, San Francisco CA, September 2, 2021. |
| 8. L.E. Klebanoff, *"Hydrogen Fuel Cell Technology: A Brief Introduction,"* Presentation to Entertainment Industry Facility Leads, Online Meeting, October 13, 2021. |

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