FINAL REPORT

Marine Engine Testing and Emissions Laboratory (METEL)

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Hydrogen Injection Project

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Overview

Concerns over fuel cost volatility, climate change and air pollution has motivated a shift to cleaner and more efficient combustion technologies for marine and stationary power production. Numerous technologies have emerged promising to address these concerns but adoption has been limited by scalability or technical barriers for robust commercial operations. Maine Maritime Academy's Marine Engine Testing and Emissions Laboratory (METEL) is collaborating with Global Marine Consulting (GMC), a technology company headquartered in Florida, to evaluate performance of hydrogen injection technologies to reduce unwanted pollutants and increase combustion efficiency within diesel engines. The technology is compact and can interface with any diesel making the technology broadly applicable to the industry. GMC is providing an auxiliary hydrogen generator which uses electrical power to low-purity hydrogen designed to be injected into the air intake manifold of diesel combustion engines. METEL will evaluate this technology on both a laboratory diesel engine and at-sea on the *R/V Quickwater*, a 41-foot coast guard class fast response vessel. The effect of hydrogen addition on the production of NO, NOx, CO and THC will be determined and engine efficiency will be monitored to assess the technology opportunities and identify potential barriers for commercial operations.

Introduction

Additives to alter the combustion behavior and pollutant formation of petroleum derived liquid fuels in diesel engines has been an active area of scientific research [1]. These additives have taken many forms and can be separated into three primary categories as outlined in Table I. Since diesel combustion kinetics are complex, the additives target combustion behavior in ways. For example, addition of the reduction additives Urea or ammonia (NH_3) to the combustion process seeks to react NO_x pollutant species to H_2O and N_2 through gas-phase reaction [2,3]. A study conducted by Larbi and Bessrour estimated that the injection of 1 vol% NH_3 into the intake air of a 1.5 MW diesel engine has the potential to reduce engine out NO emissions (g/kWh) by 11.7% and NO_2 (g/kWh) by 21%. A separate study by Lin and Lin incorporated 5 vol% of NH_3 to the aqueous-phase of an oil-water-oil three phase micro-emulsion comprising biodiesel. The resulting dissolved NH_3 concentration was 5,000 parts per million and was shown to improve diesel combustion efficiency by 1.1%, however no NOx reduction was reported and an associated increase in particulate matter emissions was observed.

Table I: Comparison of combustion additive types and injection locations currently being explored to reduce diesel engine emissions

Additive Injection Location	Additive Type	Examples
Intake Manifold	Gas	H_2, NH_3, CH_4
Fuel Tank	Liquid	NH_3, Urea, Water, Cetane modifiers
Fuel Tank	Solid	Fe_2O_3, CeO_2, PtO, CuO

Solid-phase catalysts are another additives class receiving attention for their potential to improve diesel combustion efficiency and reduce the emissions of carbon monoxide (CO), total hydrocarbons (THC) and particulate matter (PM). In this approach catalytic particles, e.g. Fe_2O_3 or PtO, are nano-dispersed within the fuel or dissolved as an organometallic solution. These additives seek to improve hydrocarbon gas-phase oxidation kinetics during combustion, as well as deposit on soot particles to promote heterogenous oxidation of solid carbon. [4-6]. For example, Zeller and Westphal evaluated the effects of two iron-based fuel additives on the sooting behavior of a 5.6L, 6-cylinder diesel engine under laboratory conditions [5]. The iron additives consisted of ferrocene and ferrous picrate which were doped to diesel fuel at levels between 0.033 and 0.33 wt.%. In this work, ferrous picrate had no reducing effect on diesel PM emissions according to smoke opacity tests of gravimetry, however ferrocene was shown to decrease PM emissions by 37%. The authors attributed this result primarily to the formation of iron-oxide deposits on internal engine surfaces which catalyzed soot oxidation. An increase of NOx emissions by 10%, however, was also observed. To better understand the anti-sooting behavior of iron-additives, Marsh et al. undertook a liquid-fed laminar diffusion flame investigation to isolate effects in the gas-phase [4]. This work showed that equivalence ratio was an important factor influencing the catalytic activity of ferrocene. Ferrocene-doped diesel fuel under lean combustion conditions suppressed soot emissions by as much as 95%; while under fuel-rich conditions, the soluble soot fraction increased resulting in an overall increase in soot mass emissions. In the latter case, fuel decomposition reactions to tars were speculated for the increased soot soluble fraction.

An economically-promising additive to reduce engine emissions is diatomic hydrogen injection into engine intake air [7-9]. Hydrogen can be efficiently supplied on-board vehicles and vessels using compact generators via electrolysis. These units are scalable and provide a constant supply of additive. Ji and Wang showed that hydrogen addition into the intake of a gasoline engine increased brake thermal efficiency from 26.4% to 31.6% at lean conditions and 6 vol.% H_2 in the intake air [10,11]. This result was accompanied by a reduction in unburned hydrocarbon (THC), carbon monoxide (CO) and carbon dioxide (CO_2) emissions by as much as 90%. The authors, however, reported increased NOx emissions by 100%, due to higher combustion temperatures. Further, efficiency improvements and carbon reductions were only realized under lean conditions; Under fuel-rich conditions both were shown to worsen.

Hydrogen injection technology has been applied to diesel engines with effects ranging from beneficial, to ineffectual, to harmful. A recent study by Pan et al. examined the effect of hydrogen addition on a 2-stroke, 12-cylinder, marine-style diesel engine on the resulting fuel consumption and emissions characteristics [8]. The generator produced up to 220 SLPM of H_2 and investigated under ISO engine test conditions of variable load and speed. The authors observed no effect of hydrogen addition on brake efficiency or engine out emissions, with the exception of idle conditions. In these conditions, the combustion is comparatively leaner and the H_2 power fraction is significant, ranging from 6.9 to 103.1 % of the fuel energy. The resulting NOx emissions were found to decrease by up to 37% with H_2 consumption at 220 SLPM, however PM emissions were found to increase by 86% offsetting the NOx reduction. Further, the use of H_2 was found to have a net parasitic loss of engine power of between 2.6% and 17.7% indicating the system was not suitable for commercial operations. Conversely, Miyamoto et al. showed that H_2 injection into a high-speed diesel engine was effective in modifying diesel firing characteristics. They showed that a 3.9 vol% injection of H_2 reduced PM and NOx emissions under EGR conditions with late injection timing [7]. This result is consistent with the reports of Zhou et al. who analyzed the effects of H_2 addition to a naturally-aspirated diesel engine at a fixed speed of 1800 RPM [9]. They showed that H_2 addition at rates up 30% of fuel energy equivalent was capable of reducing NOx and PM emissions at low and moderate load conditions. High engine loads, however, saw in increase in unregulated emissions by over 90%.

Given the variability of literature reports on hydrogen injection technology effects on diesel engine performance and emissions, Maine Maritime Academy's Marine Engine Testing and Emissions Laboratory seeks to conduct an investigation of the hydrogen injection technology in both laboratory and at-sea diesel engine testing platforms. This report summarizes the resulting diesel engine performance and emissions observations and provides an assessment of the utility of the technology to commercial operations.

Experimental Methods

Laboratory Testing Equipment and Procedures

Laboratory engine performance testing and emissions measurements were conducted on CAT C2.2L marine diesel generator. The engine is a 4-cylinder indirect injection turbocharged diesel with a bore of 84 mm and stroke of 100 mm. The engine operates at 1,800 RPM with a maximum power rating of 27 kW. The engine power was controlled and instrumented with a variable frequency drive and resistive load bank. Current and voltage sensors were used to measure load on the engine. Fuel flow is measured gravimetrically via Omega LCR-50 load cells. Intake air mass flow rate and inlet air temperature are measured with a mass airflow sensor from PMAS with 0.25% measurement uncertainty and 0.4% repeatability. Exhaust emissions ports were located several pipe diameters downstream of the turbine housing of the turbocharger. The duty cycle utilized on the CAT C2.2L test cell conformed to ISO 8178 standards and consisted of starting at idle, 100% rated engine load, 75%, 50%, 25%, 10%, and back to an idle. All load settings were maintained for a sufficient duration to achieve steady state. The GMC hydrogen production system was connected to the suction side of the turbocharger of the CAT C2.2L genset engine and operated to supply a constant stream of approximately 6 LPM of H_2 and O_2 at 2:1 molar ratio. Figure 1 presents photographs of the electrolysis cell and the installed GMC system.

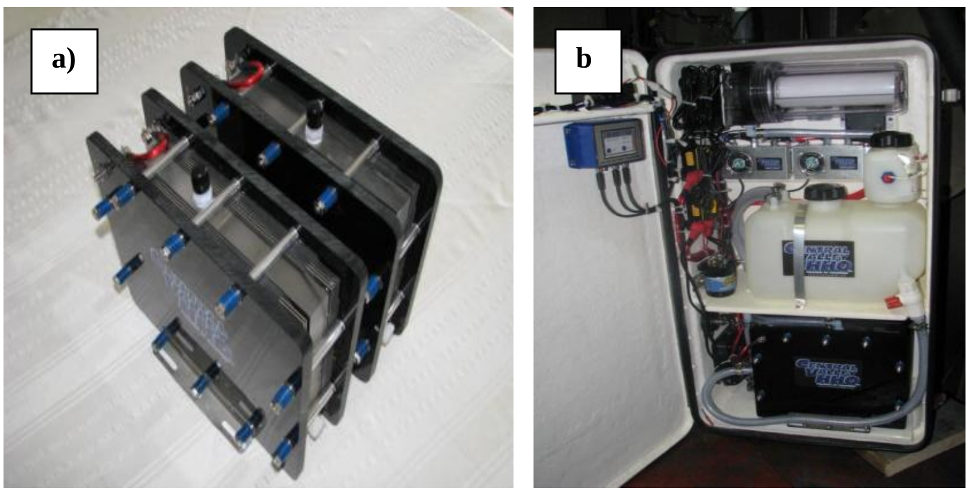

Figure 1: Photographs of the a) electrolysis cell used to produce H_2 and O_2 gas and b) the GMC hydrogen production kit including shell, water reservoir, pumps, power supply and regulators.

At-Sea Engine Testing Equipment and Procedures

Marine environment testing and emissions measurements were conducted on the research vessel *Quickwater*, a 41ft. coast Guard cutter-class workboat equipped with twin VT903 360 hp (268 kW) Cummins marine diesel engines. The dual propeller shafts were instrumented with strain gauges and Datum Electronics shaft power measurement kits to measure shaft torque, RPM, and power. Fuel flow is measured via Kral OMX-20 flow meters. Intake air mass flow rate and inlet air temperature are measured with a mass airflow sensor from PMAS with 0.25% measurement uncertainty and 0.4% repeatability. The exhaust from the port engine of the vessel was outfitted with sampling lines for monitoring gaseous and soot emissions. The sampling ports were placed 0.6 meters after the turbine housing of the turbocharger and before the water-jacketed portion of the exhaust. The duty cycle utilized on *Quickwater* conformed to ISO 8178 standards and consisted of starting idle in gear, 100% rated engine load, 75%, 50%, 25%, and back to an idle in gear. All load settings were maintained for a sufficient duration to achieve steady state. A photograph the Quickwater underway during testing is shown in Figure 2. The hydrogen generator was connected only to the port-side engine air intake during testing.

Figure 2: Photograph of the Maine Maritime Academy *R/V Quickwater* underway in Penobscot Bay during hydrogen injection performance testing.

Engine Emissions Monitoring Equipment and Procedures

Dedicated emissions monitoring equipment used during all testing included a MKS 2030 FTIR with heated sampling equipment for gaseous emissions measurements, and a BMI 1710 Mixing Condensation Particle Counter (MCPC) for soot number concentration emissions measurements. The MCPC was additionally equipped with a heated dual stage ejector pump and calibrated critical flow orifice dilution system operating at 150 Celsius and a dilution ratio of approximately 1000. All emissions and performance monitoring equipment were controlled and recorded with LabVIEW. Photographs of the Quickwater vessel and instrumentation are provided in Figure 3.

Figure 3: Photographs of floating engine emissions and data logging systems on-board the *R/V Quickwater* used during hydrogen injection performance testing.

Results and Discussion

Laboratory Engine Performance Results

The laboratory engine was fully operational at all load conditions with the hydrogen injection system operating at 6 SLPM. Engine efficiency was shown to decrease slightly as a result of the parasitic loss of the hydrogen generator as shown in Figure 4-left. The loss is within the range of the power consumption of the hydrogen generator indicating that no discernable combustion efficiency benefit was realized under the test conditions with hydrogen injection. The authors acknowledge that test conditions resulted in comparatively lower hydrogen flow, ranging from 1.4-5% of fuel energy consumption compared to literature, but is on par with the reports by Pan et al. [8]. The resulting CO emissions, Figure 4-right show a slight reduction at near idle conditions which are offset by increases at moderate to high engine loads. Figure 5 shows the NOx and Total Hydrocarbons emissions which shows a consistent elevated emissions profile for operations with hydrogen injection. Figure 6 shows PM emissions against engine load which exhibits nearly equivalent emission rates compared to no hydrogen injection.

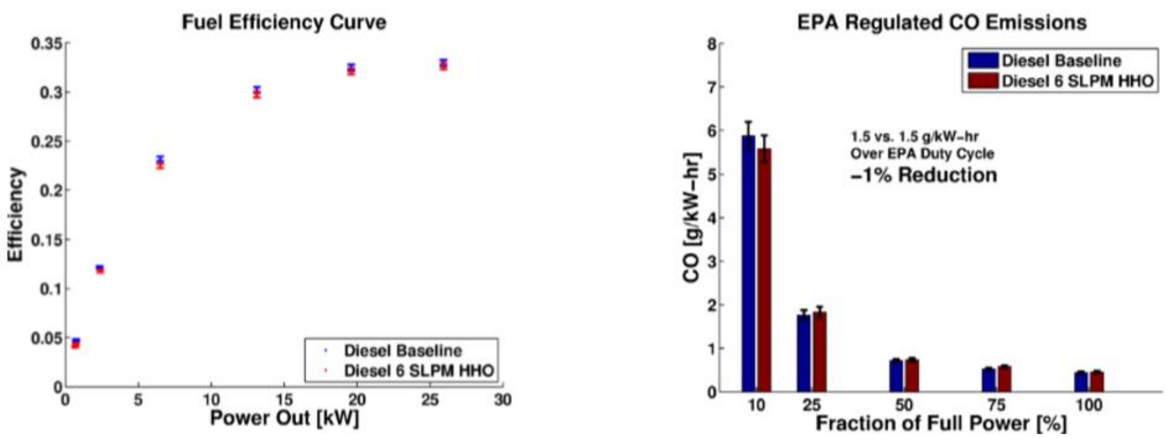

Figure 4: Thermal efficiency (left) and carbon monoxide emissions (right) versus power output on a CAT 2.2L genset. Charts include electrical power required for HHO production.

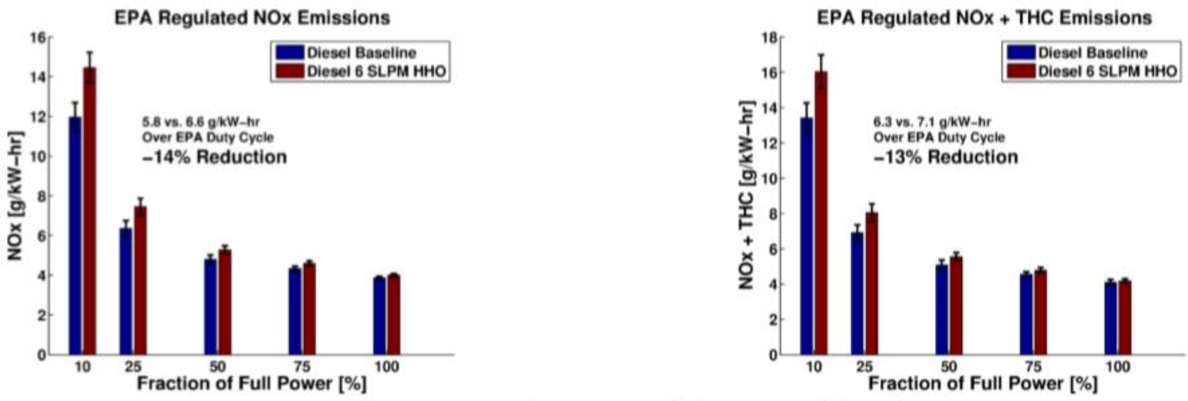

Figure 5: NOx emissions (left) and NOx + THC emissions (right) versus engine load comparing engine operations of ultra-low sulfur diesel and with 6 SLPM of H_2 on a CAT 2.2L genset.

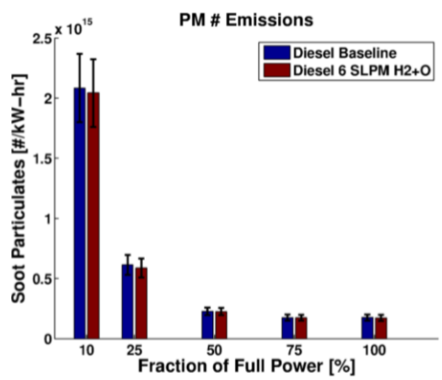

Figure 6: Particulate emissions versus fraction of full power on a CAT 2.2L genset showing nearly equivalent emissions with and without hydrogen addition.

At-Sea Engine Performance Testing on the *R/V Quickwater*

Fuel performance testing on the MMA vessel *R/V Quickwater* occurred in May 2016 in waters of Penobscot Bay just off Castine, ME Harbor. In general, the hydrogen generator performed well under at-sea conditions and performed without interruption during testing procedures. Further, the engine exhibited not directly observable performance changes while underway with hydrogen addition. Testing was completed within an 8-hr. window beginning with a baseline engine performance curve using ultra-low sulfur diesel. The hydrogen generator was then turned on and allowed to equilibrate for 30 minutes prior to performance testing. Figure 6 compares the overall fuel consumption at each engine load with and without hydrogen addition. A slight increase in fuel consumption is observed at high engine loads indicating a possible loss of thermal efficiency. These results, however, are close to instrument resolution and would require additional testing to confirm.

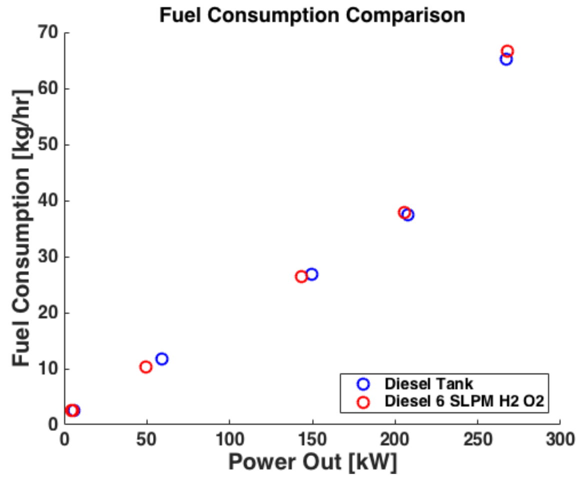

Figure 6: Fuel consumption comparison with and without hydrogen addition versus engine power output on the *R/V Quickwater*. A slight increase in fuel consumption is observed at high engine loads.

Vessel emissions remained relatively unchanged during hydrogen addition. Figure 7 compares the specific emissions rates of carbon monoxide and NOx plus THC emissions. Carbon monoxide, a particle combustion product, is shown to increase between 6-15%. This result is consistent with the results of Wang et al. who showed that liquid diffusion burning at rich equivalent ratios can increase carbon source emissions [10]. Another partial combustion product, THC, however, only exhibited a slight increase of <10% at low engine loads with nearly equivalent emissions resulting at moderate and high loads. Combining the THC emissions with NOx, as specified in the ISO emissions standards, sees an overall small reduction in the emissions rate. The reduction in THC and NOx at moderate to high engine loads with also reported by Zhou et al. [9]. Similar emission rate behavior is observed for particulate matter emissions as shown in Figure 8. Hydrogen addition produces a slight increase in the number of particles emitted is observed at low and moderate power conditions, while exhibiting reductions at high engine loads.

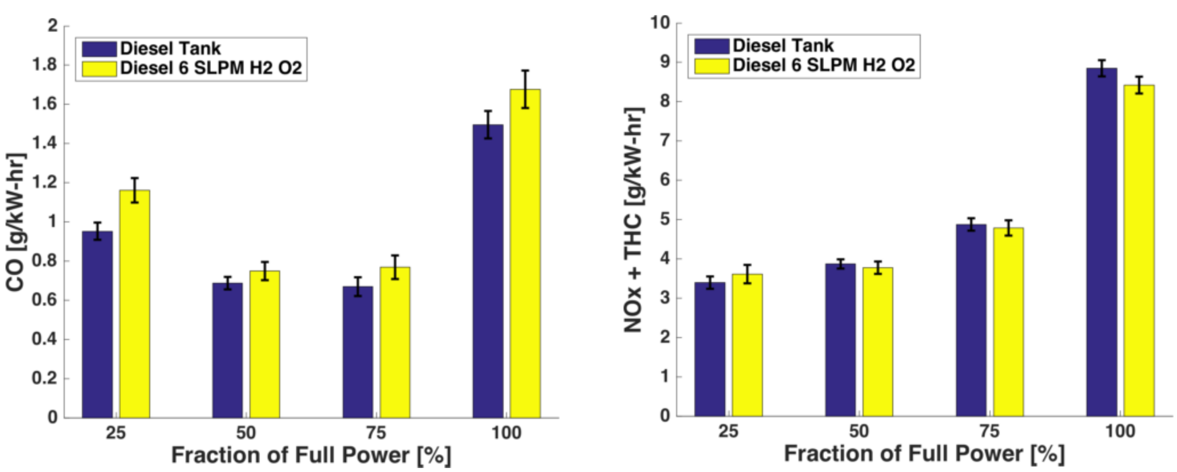

Figure 7: Carbon monoxide (left) and NOx + THC (right) emissions comparison during *R/V Quickwater* testing with and without hydrogen addition.

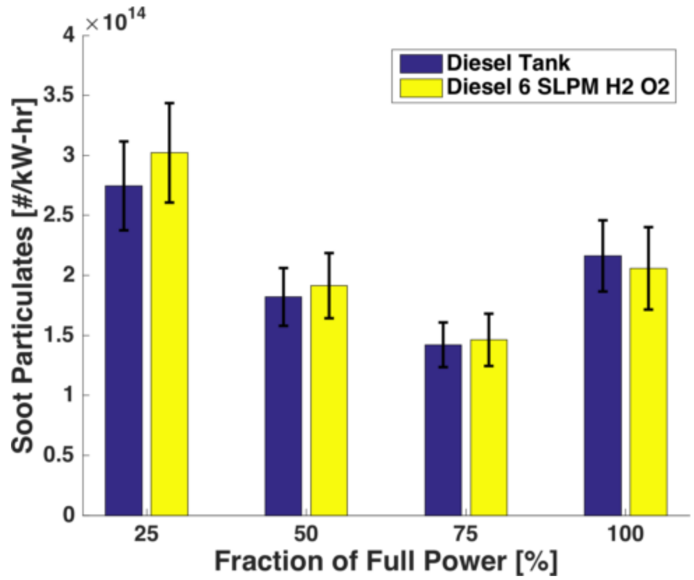

Figure 8: Particulate matter emission comparison during *R/V Quickwater* testing with and without hydrogen addition

5. Conclusions and Future Work

The performance and suitability of a hydrogen generator for H_2 combustion addition in the marine environment was detailed in a small workboat at-sea and in the laboratory. Hydrogen generator exhibited no adverse engine performance effects, however, a reduction in overall fuel economy was observed in each test condition attributed to the parasitic power consumption of the electrolysis device. At the hydrogen consumption rates supplied by the GMC device, 6 SLPM (1.4-4.8% of fuel energy), unwanted combustion products were nearly equivalent to ultra-low sulfur diesel fuel, with some variation observed with engine load, however any perceived benefits or performance decreases are considered negligible. The exception was that each engine tested exhibited an increase in NOx and THC emissions at low engine loads of between 4-13%.

The authors believe under the testing conditions and hydrogen consumption rates supplied by the manufacturer, that no systematic improvement in engine performance or emissions can be claimed without additional testing. The results do indicate, and are supported by literature, that performance benefits can be realized if H_2 addition rates can be increased significantly to within 10-25% of fuel energy. This recommendation assumes that power draw of the electrolysis device and overall size of the hardware do not significantly impact the necessary allocation of space and engine interfacing hardware. Further, the authors recommend that additional testing be accomplished to determine if variable hydrogen injection rates can be accomplished to better match engine operating condition to maintain a consistent ratio of hydrogen addition to fuel energy supplied.

Additional concerns of the technology this report does not address is the possible impacts of hydrogen additional in internal engine parts, ex. material hardening, which can reduce the lifetime of engine hardware. The risk of possible hydrogen explosions in confined engine compartments is also a concern, especially if the hydrogen generator is auxiliary powered and not switched on/off with engine start switch circuitry. Lastly, all testing was performed under fair weather or laboratory conditions. The authors recommend that long-term durability of the device be monitored under commercial operations to ensure no adverse effects under variable sea and weather conditions.

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