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Kilowatt-Scale Fuel Cell Systems Powered by Recycled Aluminum

Presented here is a novel system that uses an aluminum-based fuel to continuously produce electrical power at the kilowatt scale via a hydrogen fuel cell. This fuel has an energy density of 23.3 kW h/L and can be produced from abundant scrap aluminum via a minimal surface treatment of gallium and indium. These additional metals, which in total comprise 2.5% of the fuel's mass, permeate the grain boundary network of the aluminum to disrupt its oxide layer, thereby enabling the fuel to react exothermically with water to produce hydrogen gas and aluminum oxyhydroxide (AlOOH), an inert and valuable byproduct. To generate electrical power using this fuel, the aluminum–water reaction is controlled via water input to a reaction vessel in order to produce a constant flow of hydrogen, which is then consumed in a fuel cell to produce electricity. As validation of this power system architecture, we present the design and implementation of two proton-exchange membrane (PEM) fuel cell systems that successfully demonstrate this approach. The first is a 3 kW emergency power supply, and the second is a 10 kW power system integrated into a BMW i3 electric vehicle. [DOI: 10.1115/1.4046660]

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1 Introduction

With double the energy density of diesel and its high abundance, scrap aluminum has potential as a viable fuel source for supplementing or altogether replacing fossil fuels in many applications. Recently developed methods for extracting the embodied chemical energy of aluminum allow it to be used for power generation in circumstances where space is constrained and energy density is key or where scrap aluminum is abundant and cheap.

To extract energy from aluminum, it must be oxidized by air or water; however, when exposed to air or water containing dissolved oxygen, an oxide layer typically forms immediately on the surface of aluminum, making it functionally inert. Several methods have been developed to bypass this surface oxide layer, including ball milling aluminum into combustible powders [1,2], alloying it with rare metals [3], and eroding it with strong acids [4]. The combustion hazards of aluminum powders, the high cost of alloying metals, and the safety concerns of working with strong acids, however, have kept aluminum-based fuels from being widely implemented in commercial or consumer power systems.

In recent years, new methods have been developed that make the production of aluminum fuels significantly safer and cheaper. In particular, the development of aluminum fuels that use only small amounts (2–5 wt%) of alloying metals [5], or that use weak acids and bases for erosion [6], has contributed to pushing aluminum into the spotlight as a highly energy-dense fuel source. Using these methods, activated aluminum can be reacted exothermically with water, producing hydrogen and aluminum oxyhydroxide (AlOOH) via the following reaction:

$$2Al_{(s)} + 4H_2O_{(l)} \rightarrow 3H_{2(g)} + 2AlOOH_{(aq)} + Q \tag{1}$$

This reaction "releases" the embodied enthalpy of the aluminum fuel (859 kJ/mol Al) as a mix of thermal energy and enthalpy stored in the hydrogen product (i.e., the heating value of hydrogen) in approximately equal proportions [7]. Consequently, in terms of power generation, this fuel and its accompanying reaction with water can be considered as both a heat source and a means of storing hydrogen at 5–11 wt%, depending on whether the water is transported with the fuel or harvested in situ.

Building off the development of safer and cheaper aluminum-fuel production methods, this paper presents the design and implementation of two kilowatt-scale fuel cell systems powered by aluminum. These systems produce electricity via proton-exchange membrane (PEM) hydrogen fuel cells, allowing them to operate silently and with a balance of plant of comparable mass and volume to that required for the equivalent gasoline and diesel generators. Additionally, the reaction of aluminum with water produces no greenhouse gases or toxic emissions, making these systems usable indoors with minimal risks to human health and safety. Finally, the systems presented here were powered using aluminum fuel treated via the Slocum method [8], which has been shown to produce fuel with a shelf life of several years. This storage capability is significantly longer than that of gasoline and diesel fuel which is highly advantageous for such applications as emergency power systems where use is infrequent and often unanticipated.

2 Water-Reactive Aluminum Fuel

2.1 Preparation. To prepare the water-reactive aluminum fuel used in this research, pure aluminum pellets, 5 mm in diameter, are exposed to a eutectic mixture composed of 80 wt% gallium and 20 wt% indium heated to 120 °C as per the technique developed by Slocum [8]. After some time, the gallium and indium fully penetrate the grain boundary network of the bulk aluminum, enabling it to react with water to >95% completion based on the reaction in Eq. (1). For this formulation, achieving this high reactivity value requires a minimum eutectic mass fraction of 2.5–5 wt%, which can be controlled via exposure time [9]. After the activation process is complete, the excess eutectic is spun off and reused.

2.2 Cost Estimate. The cost of this aluminum fuel can be estimated using the most recent data from the Mineral Commodity Summaries (MCS) published by the United States Geological Survey [10]. Using market price data for bulk aluminum, gallium, and indium provided by the 2019 MCS report, the activated aluminum fuel is estimated to cost $11.90/kg, assuming that none of the Ga–In eutectic is recovered and that the cost of the materials dominates the total fuel cost. It is important to note, however, that the eutectic acts primarily as a catalyst in the aluminum–water reaction and can therefore be recovered after the aluminum–water reaction is complete and recycled to make new fuel. Accordingly, assuming

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that 95% of the eutectic can be recovered and reused, this fuel price drops to \$2.88/kg. This cost equates to \$1.64/kWh using the kilowatt-scale aluminum-fueled power system presented in this paper with a total system efficiency of 20% (further discussed in Sec. 3.1.7), compared with \$0.20/kWh for the equivalent diesel generators [11]. The cost of the aluminum fuel can be significantly reduced further to \$0.82/kWh if scrap aluminum at a price of \$1.01/kg is used instead [12].

3 Kilowatt-Scale Power Applications

To demonstrate the efficacy of utilizing this aluminum fuel, two power systems were designed and built. The first was a 3 kW emergency power supply, and the second was a 10 kW power system integrated into a BMW i3 electric vehicle. The 3 kW and 10 kW systems each operate using the same high-level component topology shown in Fig. 1. In both systems, aluminum is reacted with water via Eq. (1) in a batch reaction chamber. This reaction produces hydrogen gas that is fed into a PEM fuel cell to generate electricity, which supplies power to the overall system via a battery bank and accompanying charge controller. In the case of the 10 kW BMW system, the electrical power output from the fuel cell is additionally connected through a boost converter and used to directly charge the internal batteries of the electric vehicle. The thermal energy released by the aluminum–water reaction in either system is dissipated across a radiator as waste heat.

3.1 Three Kilowatt Emergency Power Supply. The expressed goal of the 3 kW aluminum-fueled emergency power supply was to reduce the total system energy density (energy per unit volume) of the equivalent state-of-the-art diesel generators in order to develop a system that could be more efficiently stored for disaster preparedness or shipped to remote locations. To this end, a power system that leverages the high energy density of the aluminum fuel described previously in Sec. 2 was developed. This power system consists of two separate modules: a reactor module as shown in Fig. 2 and a power conditioning and energy storage module. Here, the electrical output of the fuel cell in the reactor module connects directly to the power conditioning module. The design details of each module are presented here.

3.1.1 Aluminum–Water Reactor. In order to produce 3 kW of electrical power, the PEM fuel cell used in this power system requires a hydrogen supply rate of 40 slpm. From the stoichiometry shown in Eq. (1), it is therefore necessary to run the aluminum–water reaction at 30 g Al/min. To meet this required reaction rate, water must continuously reach the activated aluminum fuel at a flowrate of 40 mL/min. For design simplicity, the reaction system utilizes a single batch reactor, which contains enough fuel for an hour of operation (1.8 kg). In operation, activated aluminum fuel pellets are placed inside the chamber in an internal mesh basket to contain the waste AlOOH reaction product. The lid to the chamber is sealed, and water is pumped into the bottom of the chamber from the primary water line using a diaphragm pump. The reaction proceeds to produce hydrogen gas, AlOOH, and heat. The AlOOH waste product collects in the chamber's inner mesh lining and is emptied at the end of the cycle. At full power, the heat released from the exothermic reaction boils off 75% of the water entering the chamber, thereby removing this heat from the chamber as the latent heat of the excess water, as is described in further detail in Sec. 3.1.4.

The specifications of the reaction chamber itself are driven by the reaction products and reaction conditions. First, because of the nature of this activated aluminum–water reaction, the chamber material must be resistant to embrittlement by both hydrogen and gallium. Second, it was empirically determined that the batch reactor should be at least three times larger by volume than the initial amount of fuel to ensure that the reaction is not stifled prematurely by compaction of the AlOOH byproduct [8]. Finally, because the thermal management system relies on heat transfer via boiling off excess water, the reactor must be able to withstand temperatures up to the saturation temperature of water at a maximum system pressure of 2 bar (up to 120 °C) for extended periods of time. These specifications consequently drove the design of a custom 316 stainless steel reaction chamber with a total internal volume of 5 L, which could accommodate roughly 6 kg of aluminum fuel. The chamber was constructed by welding pipe flanges onto a pipe segment with an outer diameter of 6.25 in. Two 1/4 in. Swagelok tube fittings were welded onto the reactor as inlet and outlet ports.

3.1.2 Reaction Controls. With this system design, the only controllable input to adjust the hydrogen production rate is water flow into the reaction chamber. This makes controlling the system especially difficult because the reaction dynamics are highly nonlinear as a function of pressure, temperature, geometry, and fuel distribution within the reaction chamber. Our approach for this initial prototype was to apply a simple proportional-integral-derivative (PID) controller to the pressure in the reaction chamber. The goal is to keep the pressure in the system high enough for the fuel cell to produce the necessary power. It is important to note here that this simple approach is only feasible if the reaction chamber is hot enough to be able to neglect the reaction kinetics as a first-order

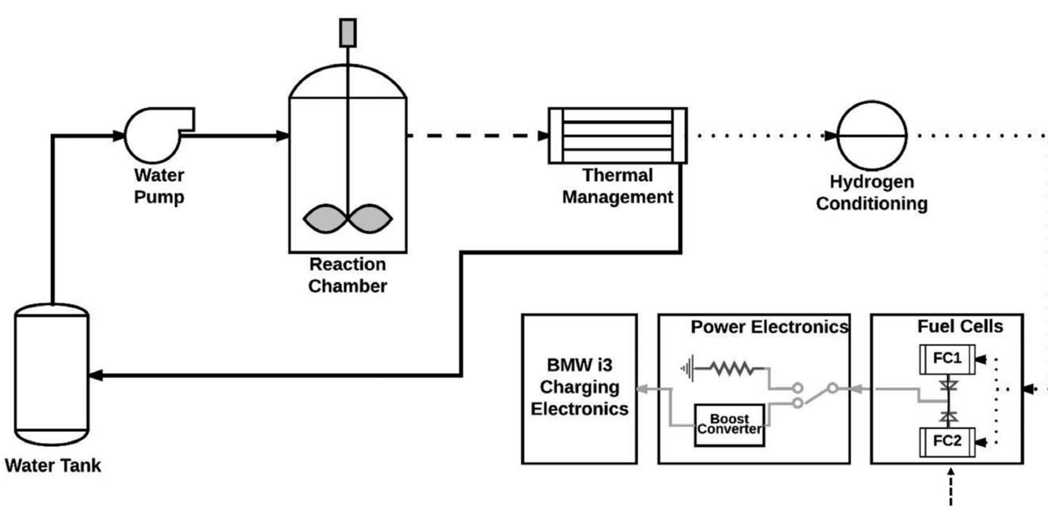

Fig. 1 High-level system topology for the aluminum-powered fuel cell systems discussed in this paper

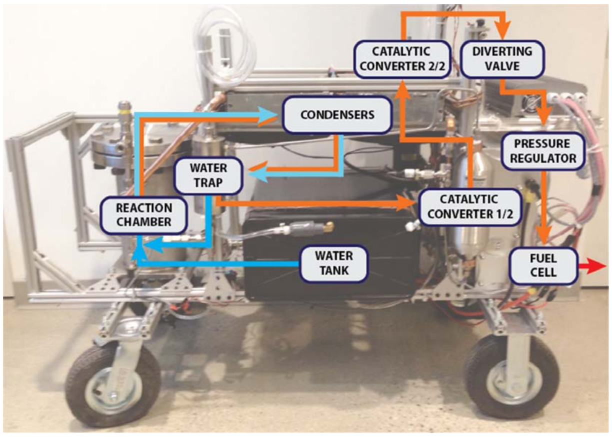

Fig. 2 Total system layout for the 3 kW emergency power supply. Not shown here is the ambient air intake vent for the PEM fuel cell.

approximation and if the power draw from the fuel cell is known and constant.

It was observed that for this aluminum fuel formulation, the hydrogen production rate is indeed constant after an initial start-up period and while there is sufficient fuel and water to sustain the reaction. It is hypothesized that this is due to the fact that as the AlOOH byproduct is produced and expands, it distributes unreacted aluminum fuel fragments throughout its low-density foam-like structure. Consequently, the rate limiting timescale in this regime is the diffusion of water throughout the AlOOH, which goes as l^2/D, where l is the characteristic length associated with the AlOOH volume and D is the diffusivity of water in AlOOH. Given that l here is constrained by the dimensions of the reactor and therefore held roughly constant, the reaction dynamics present themselves as roughly linear in the steady-state operating regime, and thus, the use of a simple PID controller to hold hydrogen pressure constant is reasonable.

The aluminum–water reaction also exhibits a start-up transient that results from starting the reaction at low ambient temperatures. Because the reaction rate follows the typical Arrhenius exponential rate law, at low temperatures, the reaction kinetics become the limiting timescale. In operation, a start-up routine initially pumps 100 mL of water into the reaction chamber and then waits until the temperature reaches near 100 °C. The built-up hydrogen from this start-up process is purged via a controllable valve in an effort to purge the system of oxygen and other gases present in the system from the refueling process. Once the system is warmed up, the control scheme shown in Fig. 3 is used to stabilize the system pressure during steady-state operations.

In this early prototype, feed-forward control was utilized to appropriately bias the controller input based on knowledge about the expected power draw in order to handle transients during simple load following. In the majority of operating conditions, however, most significant load fluctuations are handled by the on-board battery bank, described in further detail in Sec. 3.1.5. With the batteries handling load spikes, the primary function of the fuel cell is to constantly recharge the batteries. The required power output of the fuel cell can therefore be inferred by the state of charge of the battery bank, informing the controller of an appropriate water flowrate set point around which the system pressure could be stabilized.

In order to inform the control subsystem and ensure that the overall system operates safely and efficiently, a number of sensors relay information back to the primary CPU controlling the system. The reactor is outfitted with a pressure transducer as the primary feedback for the reaction controller, as well as thermocouples at both the inlet and outlet of the reaction chamber to monitor the reactor temperature (especially during start-up) and the output hydrogen and steam mixture, respectively. Additionally, because the system relies on gravity to separate the condensed water from the hydrogen stream (see Sec. 3.1.4), an accelerometer is used to detect that the reactor module is at a suitable orientation for safe operation. If the orientation of the reactor module goes outside this range, all pumps shut off and the system is purged of hydrogen.

3.1.3 Hydrogen Conditioning. Hydrogen must be supplied to the fuel cell within a relatively narrow range of temperatures and pressures as specified by the fuel cell manufacturer. Additionally, this hydrogen must be stripped of oxygen, water, and other gases that are potentially harmful to the platinum catalyst of the PEM fuel cell used in this power supply. The radiators, described in further detail in Sec. 3.1.4, have the dual purpose of cooling the hydrogen and removing excess steam from the product stream coming from the aluminum–water reaction system.

After the radiators condense the saturated steam, gravity is used to separate out the condensed liquid water, and what remains is a mixture of hydrogen and trace amounts of carbon dioxide, nitrogen, and oxygen, all at a relative humidity of 100%. Carbon dioxide, nitrogen, and oxygen are initially present due to the system being open to air during fuel refilling; however, during start-up, the first several liters of hydrogen are purged to the atmosphere after the aforementioned start-up routine, thereby significantly reducing the remaining concentration of carbon dioxide, oxygen, and nitrogen.

In steady-state operating conditions, dissolved oxygen in the input water for the reaction system is continually released into the hydrogen stream. To scrub the product stream of oxygen, catalytic converters with a palladium catalyst remove the remaining oxygen by promoting its reaction with hydrogen to produce water vapor. This vapor and any other remaining vapor is then removed from the input stream via an in-line desiccant, as indicated in Fig. 2 as “CATALYTIC CONVERTER 2/2” and in Fig. 4 as “Filter.” Once dry and devoid of oxygen, the remaining room-temperature,

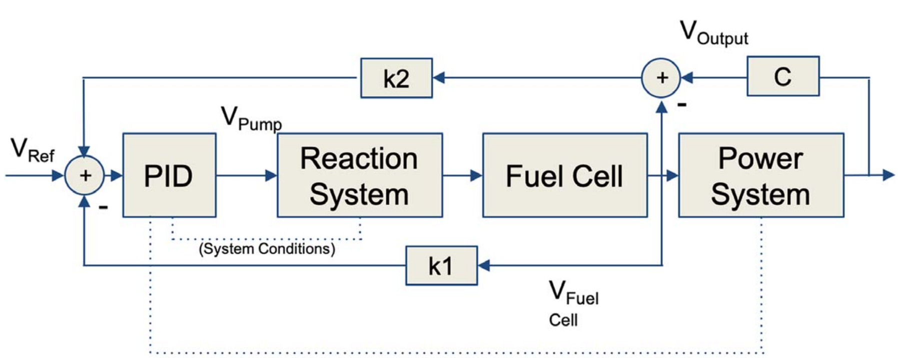

Fig. 3 Control system diagram for the reactor in the 3 kW emergency power supply

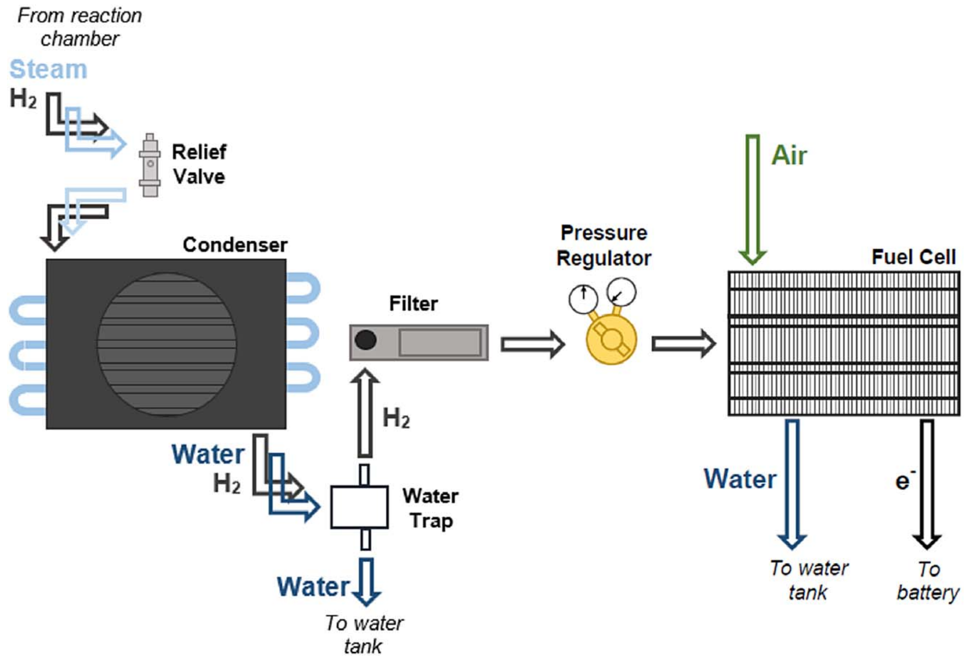

Fig. 4 System diagram for the 3 kW emergency power supply's hydrogen conditioning subsystem

pure hydrogen gas is passed through a pressure regulator that maintains a constant pressure of 0.5 bar (gauge) at the inlet of the fuel cell.

3.1.4 Thermal Management. At steady-state operating conditions, this power system dissipates a significant amount of thermal energy generated both at the reaction chamber and the fuel cell. In the reaction chamber, the reaction between aluminum and water is highly exothermic ($\Delta H_{rxn} = 430$ kJ/mol Al at 100 °C), with roughly half of the initial embodied enthalpy of the activated aluminum fuel being released as heat. The remaining energy is converted to enthalpy stored in the gaseous hydrogen evolved from the aluminum–water reaction (429 kJ/mol Al[2]). Given the required hydrogen flowrate of 40 slpm, the reaction system must react 0.017 mol Al/s, resulting in 7.31 kW of waste heat at the reactor.

To manage this heat release, excess water is pumped into the reactor, where it boils off into steam, carrying with it the excess thermal energy as latent heat. This steam subsequently passes through two car radiators (BAE Systems 70-05428 Humvee Rear A/C Evaporator Coil) in series, each with external forced air convection provided by fans operating at volumetric flowrates of 0.52 m^3/s. The steam is condensed in these radiators and the latent heat is carried away with the air exhaust. The hydrogen is separated from the liquid water via a simple gravity-operated water trap. An ultrasonic water level sensor is used to detect the buildup of water at the bottom of the water trap and accordingly sends a signal to the main controller to activate a separate diaphragm pump that recirculates the water back into the reaction chamber.

Thermal energy must also be dissipated at the hydrogen fuel cell. The fuel cell's 40% electrical energy conversion efficiency means that another 4.5 kW of heat must be dissipated at the fuel cell stacks during 3 kW steady operating conditions. To this end, we found that the stock fans on the fuel cell were sufficient for maintaining allowable stack temperatures of 65 °C. The fuel cell was carefully mounted on the reactor module structure so as to allow adequate airflow to the fans.

[2]This value is computed using the higher heating value of hydrogen and the stoichiometric ratios given in Eq. (1).

3.1.5 Electricity Generation. The target steady-state electrical power draw for this system was specified as 3 kW at 120 VAC. To meet this demand, a Horizon H-3000 PEM fuel cell was chosen for generating electrical power from the hydrogen product of the aluminum–water reaction. This fuel cell was chosen for its nameplate efficiency of 40%, ability to operate with ambient air at temperatures between 5 and 30 °C, and integrated self-humidification system that brings the reactants to the required relative humidity without any additional hardware. The output of the fuel cell varies between 35 and 65 VDC by the polarization curve shown in Fig. 6. In order to meet the specified power requirements without compromising the system's ease of deployment and desired ruggedness for emergency applications, a physically separate electronics systems enclosure was designed and fabricated. This system is composed of three primary components: a battery pack, charge controller, and a DC–AC inverter. Combined with various sensing and voltage regulation equipment, this system meets both the 120 VAC load at four ground fault circuit interrupter (GFCI) outlets and power requirements for the 12 VDC controllers, auxiliary equipment (i.e., pumps, fans, etc.), and fuel cell controller of the reactor system. Figure 5 shows the connection diagram for this electrical system.

The battery pack for this system is crucial for handling load peaks without having to directly ramp up the reaction rate in the reaction subsystem. The pack chosen for this prototype system is composed of 16 lithium ion batteries, each with 20 A h capacity and cell voltage of 3.2 VDC, wired in series, which result in a total pack voltage of 51.2 VDC. At full charge, this pack can supply 3 kW for roughly 20 min. Though this pack is rated for continuous discharge at 100 A, the current was intentionally capped at 70 A with a breaker in series on the negative line to increase the safety factor given the 3 kW power specification. The pack is further protected by a balancing board with an 80 A over-current protection. A charge controller is used to step down the voltage of the fuel cell output to the optimum charging voltage of the battery pack based on the temperature and state of charge of each cell. For this purpose, an Outback Power FLEXmax 80 charge controller was chosen given its high efficiency (97.5%) and programing flexibility. Finally, an inverter is used to convert the varying DC output voltage of the fuel cell to 120 VAC 60 Hz to be compatible with most standard appliances and electronic devices in the US. Here, a Voltech HT-S-3000 inverter was chosen for this application.

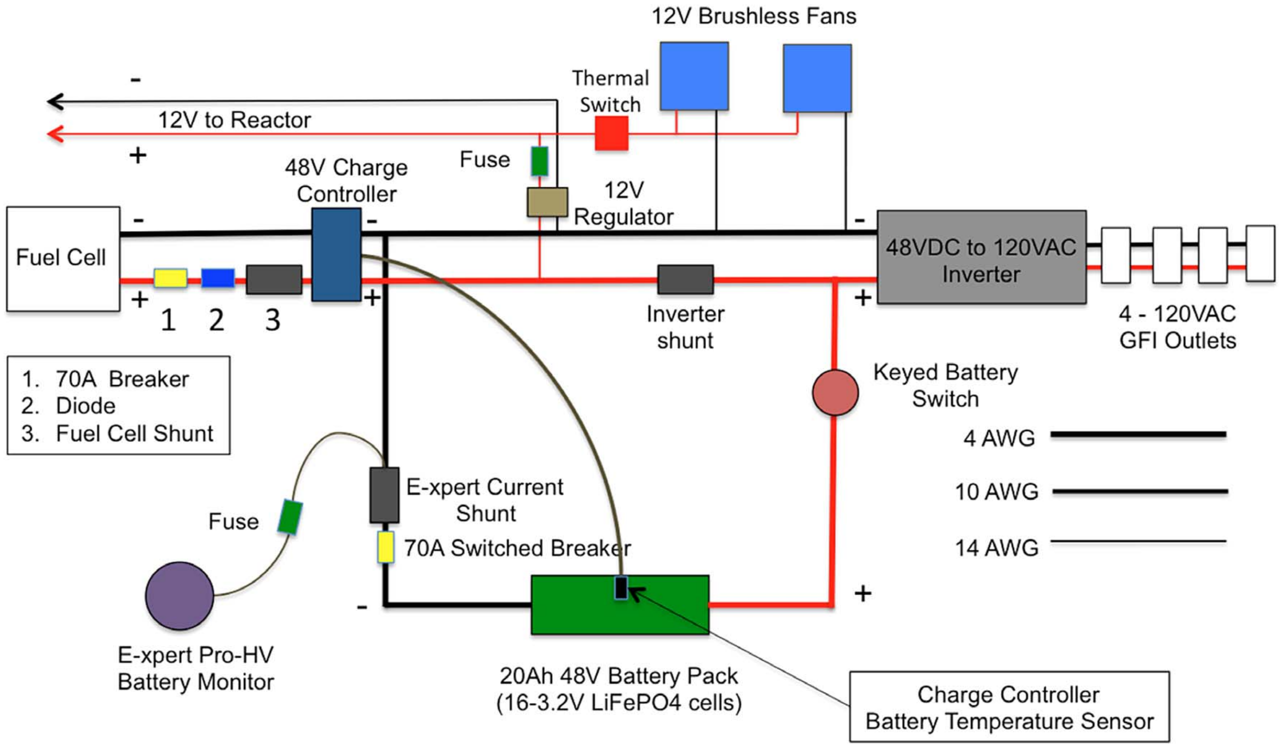

Fig. 5 Electrical subsystem component layout for 3 kW emergency power supply

3.1.6 System Integration. The reactor module is built on a 1.2 m by 0.6 m by 1 m frame composed of 80/20 T-slotted aluminum extrusions, chosen for ease of construction and strength/weight requirements. In the final prototype assembly, the 80/20 extruded bars were fastened together using three standard 80/20 parts: braces, tee plates, and right-angle brackets. Four air-ride casters 20 cm in diameter enable safe transport of this module. Key components like the fuel cell and reactor are additionally shock mounted using soft rubber spacers to minimize vibration during operation and transport.

Where possible, the tubing used to connect various components in the reactor module is 316 stainless steel connected via Swagelok tube fittings, which create a gas-tight metal–metal seal. The primary exception to this is the radiator used in the thermal management subsystem. For this prototype, prefabricated car radiators made from copper tubing were used as a proof-of-concept. It is noted here that copper is susceptible to hydrogen embrittlement and these components will therefore would need to be replaced in future iterations.

The power electronic components are enclosed in a Pelican iM3075 transport case, separate from the reaction system. The mounting structure was fabricated to the case's dimensions using 20 mm square 80/20 extrusions, which were then assembled using the appropriate brackets. The structure is composed of two nested inner and outer sub-structures. The former is attached directly to the case and is used to mount the panel onto the top of the power electronics module. The latter is shock mounted to the external structure using four rubber vibration/damping mounts each rated for 59 kg. Each component was individually mounted to the internal 80/20 structure, considering the operating requirements, such as ventilation and electrical insulation requirements. These include but are not limited to a 2 cm clearance on the fan end of the inverter and proper air circulation across the battery pack and charge controller.

There are two connections between the reactor module and the power electronics module. The first connection is the 48 VDC line from the fuel cell to the power electronics box, and the second is the 12 VDC line from the power electronics module to the reactor module. This line provides power to all of the auxiliary equipment via a buck converter that steps the voltage from 48 VDC down to 12 VDC. Current is sensed on the positive line of both the fuel cell and the inverter input using sense current shunt resistors and an optically isolated sensing circuit.

3.1.7 Performance. The 3 kW power system was able to stably produce power over the target operating period of 1 h at the target 3 kW load. Given the slow aluminum–water reaction rate at start-up, several minutes were typically required for the system to come up to a suitable temperature for steady operations. Starting the controller with a cold system results in a significant pressure spike due to the considerable time lag between the water input and associated hydrogen generation. In operation, the start-up routine does not affect basic functionality of the system, as the batteries have adequate capacity to supply the full power during this initial idle period.

The final mass and volume of this power system are on par with the equivalent diesel-powered system. In total, the system-wide efficiency of the prototype is only 20% given that half of the energy released from the aluminum–water reaction is dumped as waste heat, the fuel cell is 40% efficient, and additional energy is required for pumping water at low flowrates into the reactor, driving the cooling system, and powering monitoring electronics. The system-wide energy density is further decreased when taking into consideration the amount of water required to run this reaction; however, this can be neglected if water is available on site.[3] Compared with modern diesel generators that can achieve efficiencies of 40–50% [14], the efficiency of this system does not compare well; however, the fuel itself is two times more energy dense than diesel, and therefore, the volume of fuel required is comparable in both systems. The aluminum-powered system offers the additional benefits of being able to be run inside, operate quietly, and function as a safe heat source for cooking, sterilization, or desalination/water

[3]It has been found that this reaction can proceed with brackish water, so the availability of water is a reasonable assumption in many applications.

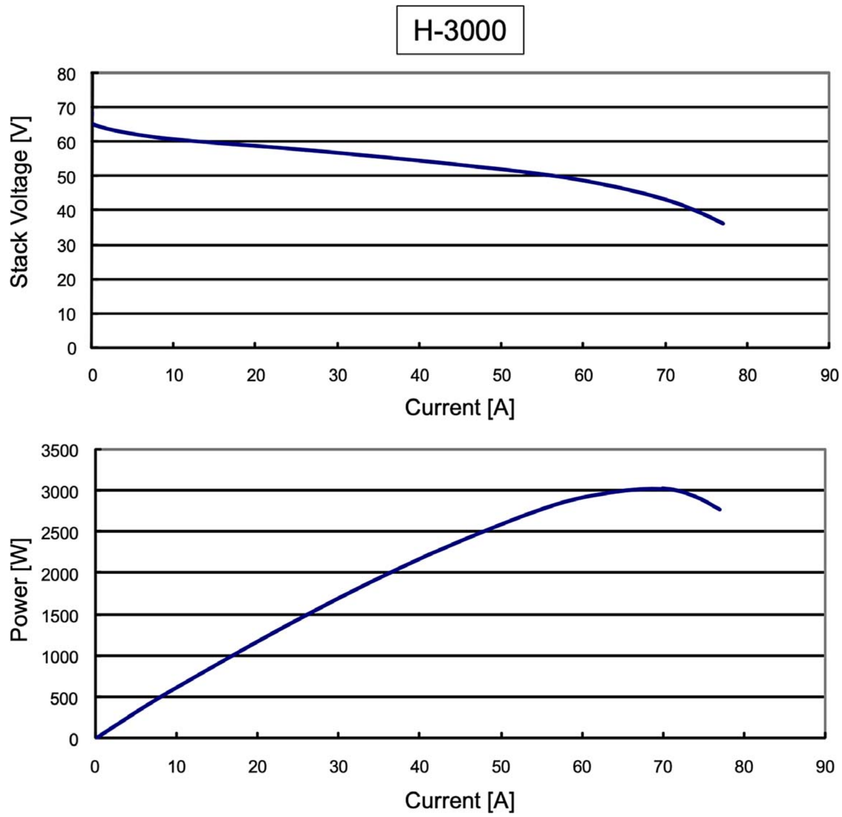

Fig. 6 Polarization curves for the Horizon H-3000 PEM fuel cell used for the 3 kW power system [13]

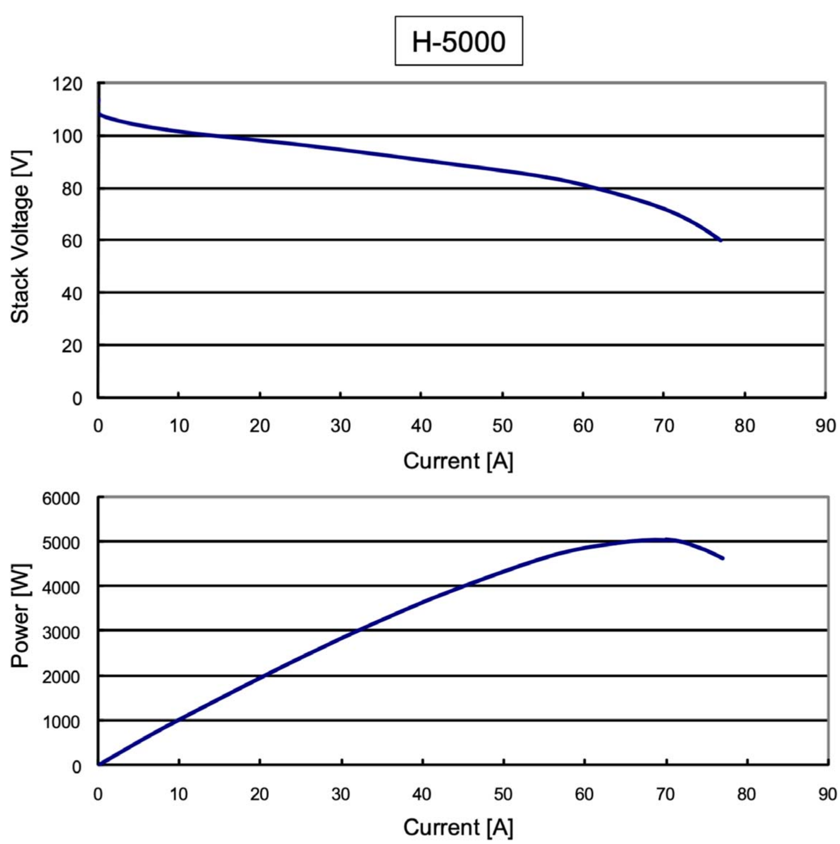

Fig. 7 Polarization curves for the Horizon H-5000 PEM fuel cell used for the BMW i3 power system [15]

purification, further increasing the total system efficiency where these applications are necessary.

3.2 Powering a BMW i3. After proving the capabilities of aluminum fuel in a 3 kW power supply, an even higher power output system was targeted for demonstrative purposes. To this end, a 10 kW aluminum-fueled power system was designed, built, and installed inside a BMW i3 to charge the vehicle's battery. The primary challenges of this application were those of scaling up the reaction chamber and heat dissipation capabilities while maintaining a controllable system with a small footprint, as well as challenges of integration into the BMW i3 itself.

3.2.1 Handling Increased Power. This system is powered by two Horizon H-5000 5 kW PEM hydrogen fuel cells that each operate at a maximum efficiency of 40%. Figure 7 shows the polarization curves for this particular model. In order to operate these fuel cells at full capacity, a steady hydrogen flowrate of 120 slpm is required. Similar to the 3 kW system, this hydrogen is produced on demand through the continuous reaction of 1.7 g of aluminum with water each second. By producing the hydrogen on demand and immediately consuming it in the fuel cells, this system circumvents the numerous safety and logistical challenges associated with pressurized hydrogen storage for automotive energy storage. Achieving a steady aluminum–water reaction at this high rate required the implementation of a new PID controller to regulate the water input to the reaction chamber. Additionally, a mixer was added to minimize the effects of AlOOH buildup within the reaction chamber and to ensure that new water could easily reach unreacted fuel within the chamber.

While producing 120 slpm of hydrogen, this aluminum water reaction also releases 28 kW of thermal energy. It is therefore imperative that the system be capable of effectively dissipating this heat to ensure the safety of the system and passengers. Additionally, the PEM fuel cells used require that their hydrogen input be below 40 °C. The heat dissipation within this system is done using a two-stage cooling design that takes advantage of the car's internal radiator as outlined in Fig. 8. In this system, a mix of pressurized hydrogen and steam leaves the reaction chamber at 120 °C. The gas is then passed through an initial high temperature heat exchanger that cools the gas to approximately 85 °C, condensing most of the water vapor. With the majority of the water removed, the remaining gas is primarily hydrogen and of significantly lower thermal mass, allowing it to be easily cooled to 40 °C in the second heat exchanger. The water condensed through both of these cooling stages is then recycled back into the system's water tank. Using this two-stage cooling system ensures that the hydrogen is cooled to the requisite 40 °C and allows the majority of the heat transfer to occur in the first heat exchanger where the large temperature difference between the gas and coolant fluid ensures higher thermodynamic efficiencies.

3.2.2 System Integration. The final prototype 10 kW power system shown in Fig. 9 weighs approximately 230 kg when fully fueled. While this is within the cargo capacity of the vehicle, for a mass this large, all major components were mounted to designated structural hard points within the car. This ensures that the system was secured in place even while driving at highway speeds, and that the installation and mounting of the system would not compromise the structural integrity of the vehicle.

As previously discussed, the thermal management subsystem takes advantage of the car's internal radiator. The cooling capacity of the car's standard radiator is sufficient to handle the added thermal load of the reactor system; however, temperature sensors in the coolant line are also used to ensure that the coolant fluid is not being heated to dangerous levels during system operation. To install the thermal management subsystem, the stock coolant loop for the car was cut and diverted to two additional heat exchangers as outlined in Fig. 8. These heat exchangers are placed at high points within the car as they are used to condense water that is then drained downwards via gravity. While effective, these additions caused the coolant loop to have higher pressure losses, and the car's internal coolant pump was unable to pump the coolant at a sufficient rate to cool the system. To combat this, a supplemental pump was added to the loop as well as a pressure gauge to accurately control the flowrate and pressure within the coolant loop. With these additions, the coolant successfully flows through the car's standard coolant loop as well as the additional heat exchangers at a sufficient flowrate for effectively cooling the hydrogen stream.

Electrical integration into the BMW is composed of both high and low voltage power lines. The high voltage line connects the 10 kW power system output to the BMW battery charging system at approximately 350 V. This is done using a boost converter to increase the voltage from approximately 90 V coming out of the Horizon fuel cells to the voltage of the BMW's battery, which varies from 260 to 400 V depending on its state of charge. This power is delivered directly into the high voltage bus located in the BMW's Electrical Machine Electronics (EME) module. The low voltage line is used to power auxiliary equipment within the power system, including pumps, fans, and relays that operate primarily at 12 V. This low voltage power is taken directly from the BMW 12 V line already integrated and made available for passengers to charge electronics. Due to the high load of the auxiliary equipment within this system (1 kW), the standard vehicle charging ports could not be used without blowing internal fuses. Therefore, a line was connected directly from the source of this 12 V power, a DC–DC buck converter located in the EME. This buck converter draws power from the BMW's main battery to charge and power its 12 V battery and has a similar role to that of an alternator in a gas-powered vehicle. Our system installed an additional line coming off of the buck converter that runs directly into the fuel cell system to power all auxiliary equipment. By integrating both the low voltage and high voltage lines from our system into the BMW, the aluminum power system can

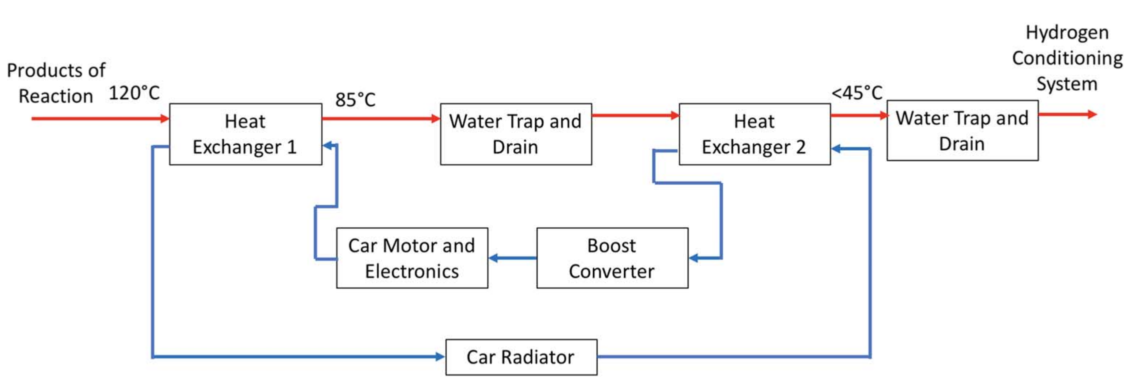

Fig. 8 Thermal management subsystem design for the 10 kW BMW power system

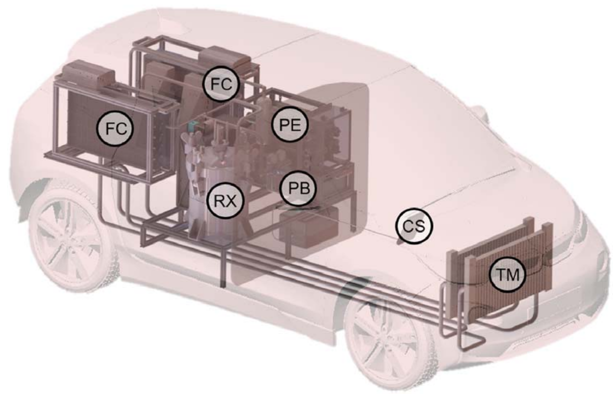

Fig. 9 Computer aided design (CAD) rendering of the entire 10 kW system integrated into the BMW i3. FC, RX, PE, PB, CS, and TM represent fuel cells, reaction chamber, power electronic, polycarbonate barrier, control system, and thermal management, respectively.

operate completely off BMW's internal power bus without the need for any additional external connections.

3.2.3 Performance. In total, the system operates safely at 10 kW steady state while maintaining steady reaction chamber pressures, and without overheating the BMW or its coolant line. Additionally, the vehicle remains fully drivable even with the system structurally integrated, and during operation, all electrical components are run completely off of the vehicle's power. As a result, this system has successfully shown that not only are high power aluminum–water reactions are possible, but that they can be used to safely generate electrical power at a 10 kW scale. Additionally, this system demonstrates the ability of such designs to easily integrate into current electric vehicles without compromising the safety of the vehicle or passengers.

4 Future Work

After validating these projects at large scale and developing these proof of concept systems, it is clear that there is still significant room for advancements in future work. First, in future iterations of this system, the system efficiency can be pushed even higher by incorporating higher efficiency fuel cells and reducing the mass and volume of the balance of plant. These initial prototype systems utilize substantial auxiliary equipment such as gas purifiers and boost converters that lowered the overall system energy density to below the levels currently targeted by the US Department of Energy for hydrogen-fueled vehicles [16]. There exists significant opportunity for miniaturization of these components.

Another major advancement may come from the development of a liquid aluminum fuel. This fuel is made by suspending large mass fractions of aluminum particles in a shear thinning oil. The resulting suspension is pumpable and water-reactive with the same levels of reaction completion as observed for solid fuel pellets [9]. The use of a liquid fuel for future power systems would allow for the fuel to be easily metered across the system eliminating the need for batch reactors. In place of the large batch reaction chambers used for both the 3 kW and 10 kW systems, small plug flow reactors can be incorporated. Utilizing a plug flow reactor would not only reduce the size of the reactor system but would also greatly simplify reaction rate control.

In each of the power systems presented here, the thermal energy released in the aluminum–water reaction is dissipated, leaving roughly half of the energy content of the aluminum unutilized. It is recommended that future work explore integrating peripheral systems that can utilize this thermal energy to power small electronics, desalinate water, or provide space heating, for example, depending on the constraints and functional requirements imposed by the application. As a result, the total system-wide efficiency would increase substantially and enable added functionality.

5 Conclusion

Presented here are the first large-scale power systems (>1 kW) powered by a novel aluminum fuel. The two system designs and prototypes described here both utilize the reaction between this aluminum fuel and water to produce hydrogen, which in turn supplies a PEM fuel cell for electricity generation. Each power system uses a simple PID controller to throttle the flowrate of water into a batch reaction chamber, which contains all of the fuel required for a typical operating period. The reaction is limited by the presence of water and thus does not pose a risk of a runaway scenario. Despite this, however, there are significant start-up and shut-down time periods as the reactor warms up and cools down in between operating periods. In both systems, the batteries supply energy during the start-up period. After this initial phase, a steady flowrate of hydrogen gas is produced and subsequently stripped of water vapor and any oxygen that may be present in the stream. Because the reactor is water cooled by pumping excess water into the reaction chamber that is vaporized by the heat of reaction, the amount of water in this hydrogen stream is significant. The stream is cooled via fan-cooled radiators, and the condensed water is separated by a gravity-driven water trap. The final pure hydrogen is sent through a pressure regulator to maintain a safe operating pressure for the fuel cell, through which the hydrogen finally passes to produce electricity.

These prototype systems show that stable power can be generated using this approach at the kilowatt scale. Compared to other fuels, the energy density of aluminum is twice that of diesel, but by dumping the thermal energy released in the aluminum–water reaction, the system-wide efficiency drops to put the system-wide energy density on par with equivalent diesel systems when only factoring in the electrical power produced. For many applications, however, thermal energy is needed for space heating, cooking, and water purification. In these applications, the system-wide energy density is much greater than that of the equivalent diesel system. Future work must be done to establish methods for utilizing the thermal output of the aluminum–water reaction to produce additional electricity for applications in which the thermal energy is not otherwise utilized.

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