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The Fuel Cell Powered Club Car Carryall

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December 2005

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The Fuel Cell Powered Club Car Carryall

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Summary

NASA John H. Glenn Research Center initiated development of the Fuel Cell Powered Club Car Carryall as a way to reduce pollution in industrial settings, reduce fossil fuel consumption and reduce operating costs for transportation systems. The Club Car Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application.

The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future aeronautics and space applications. The work was done under the Hybrid Power Management (HPM) Program, which includes the Hybrid Electric Transit Bus (HETB).

The Carryall is a state of the art, ground up, electric utility vehicle. A unique aspect of the project is the use of hydrogen powered proton exchange membrane (PEM) fuel cells as the primary power source. There are large transient loads associated with electric vehicles that require a very large primary energy source, or an energy storage system. The energy storage system can consist of devices such as batteries, flywheels, or ultracapacitors. Ultracapacitors were used for this application. Ultracapacitors are ideal for applications such as electric vehicles where long life, maintenance free operation, and excellent low temperature performance is essential. State of the art symmetric ultracapacitors were used for this application. The ultracapacitors were interconnected in an innovative configuration to minimize interconnection impedance. The combination of PEM fuel cells and ultracapacitors provides a power source with excellent energy and power density. The life of PEM fuel cells is shortened significantly by large transient loads. Ultracapacitors used in conjunction with PEM fuel cells reduces the transients applied to the fuel cell, and thus appreciably improves its life.

Another unique aspect of the project is the use of metal hydride hydrogen storage. Hydrogen is traditionally stored as a compressed gas or as a cryogenic liquid. Both of these storage methods have shortcomings that present problems for the use of hydrogen as a ubiquitous fuel gas. Hydride hydrogen storage stores hydrogen in a safe and efficient low-pressure solid form.

Innovative features, such as multiple power sources, and regenerative braking through ultracapacitor energy storage, are planned. Regenerative braking recovers much of the kinetic energy of the vehicle during deceleration. The Carryall had been tested previously with the standard lead acid battery energy storage system, an asymmetric ultracapacitor energy storage system, and will be tested with fuel cells in conjunction with an ultracapacitor energy storage system. The report concludes that the Fuel Cell Powered Club Car Carryall can provide excellent performance, and that the implementation of fuel cells in conjunction with ultracapacitors in the power system can provide significant reliability and performance improvements.

Introduction

NASA Glenn Research Center initiated development of the Fuel Cell Powered Club Car Carryall as an excellent opportunity to transfer technology from the aerospace and military industries to a commercial venture. The project is seen as a way to reduce pollution in industrial settings, reduce fossil fuel consumption and reduce operating costs for transportation systems. The Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future aeronautic and space applications.

NASA Glenn Research Center has a wealth of experience in power systems through the HPM Program. The Avionics, Power and Communications Branch of the Engineering Development Division initiated the HPM Program for the Technology Transfer and Partnership Office. HPM is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves

overall system performance and efficiency. The advanced power devices include ultracapacitors and fuel cells. HPM has extremely wide potential. Applications include power generation, transportation systems, biotechnology systems, and space power systems. HPM has the potential to significantly alleviate global energy concerns, improve the environment, and stimulate the economy.

One of the unique power devices being utilized by HPM for energy storage is the ultracapacitor. A capacitor is an electrical energy storage device consisting of two or more conducting electrodes separated from one another by an insulating dielectric. An ultracapacitor is an electrochemical energy storage device, which has extremely high volumetric capacitance energy due to high surface area electrodes, and very small electrode separation. Ultracapacitors have many advantages over batteries.

- Batteries can only be charged and discharged hundreds of times, and then must be replaced. Ultracapacitors can be charged and discharged over 1 million times. The long cycle life of ultracapacitors greatly improves system reliability, and reduces life-of-system costs.
- Long ultracapacitor life significantly reduces environmental impact, as ultracapacitors will probably never need to be replaced and disposed of in most applications.
- The environmentally safe components of ultracapacitors greatly reduce disposal concerns.
- High ultracapacitor power density provides high power during surges, and the ability to absorb high power during recharging. Ultracapacitors are extremely efficient in capturing recharging energy.
- Ultracapacitors are extremely rugged, reliable, and maintenance free.
- Ultracapacitors have excellent low temperature characteristics.
- Ultracapacitors provide consistent performance over time.
- Ultracapacitors promote safety, as they can easily be discharged, and left indefinitely in a safe discharged state.

HPM has been successfully applied to the NASA Hybrid Electric Transit Bus HETB project. This is a 40-ft transit bus with a unique hybrid drive. At over 37,000-lb gross weight, this is the largest vehicle to ever use ultracapacitor energy storage. The ultracapacitor technology utilized for the HETB is being applied to satellite actuation to replace unreliable hydraulic systems. The motor and control technology utilized for the HETB is being applied to flywheel dynamometer systems.

HPM has been utilized to provide power for drop tower research. HPM is being considered for space missions, such as the exploration of Mars, and deep space missions, such as the exploration of Europa.

Through the NASA Glenn Research Center Technology Transfer and Partnership Office, HPM is being applied to power generation, transportation, safety, and biotechnology systems. Some specific examples include photovoltaic power generation, electric vehicles, and safety systems.

NASA Glenn Research Center provides overall project coordination and is responsible for testing the vehicle. This includes instrumenting the vehicle and developing instrumentation and control programs. Wherever practical, off-the-shelf components have been integrated into the test configuration.

Objectives

Development of the vehicle was performed at NASA Glenn Research Center. Of particular interest are the practical implementation of a PEM fuel cell power source in conjunction with an ultracapacitor energy storage system, and a metal hydride hydrogen storage system. Vehicle performance should be improved from that with the standard lead acid battery power system due to significantly reduced mass. Vehicle reliability is expected to be significantly improved due to the use of highly reliable, long life power system components.

Figure 1.—Club Car Carryall

Discussion

Vehicle Description

The Carryall is a state of the art, ground up, electric utility vehicle. The vehicle is shown in figure 1 and described in detail in appendix A. The standard Carryall is a series electric vehicle. As a series electric vehicle, all power is provided to the drive wheels from an electric drive motor, powered by an electric drive system. The block diagram for the standard Carryall is shown in figure 2. The Fuel Cell Powered Carryall is also a series electric vehicle, as shown in the block diagram in figure 3.

The standard energy storage system consists of six 8 volt, 150-amp hour sealed lead acid, deep discharge batteries to store electrical energy. The complete battery pack is shown in figure 4. The battery pack is installed beneath the seat on the interior of the vehicle. The seat is removed for battery maintenance, which is required weekly. Maintenance includes inspecting the electrolyte level, and adding electrolyte as required. The battery charger is an off board unit. The charger is rated at 48 volts, 17 amps DC.

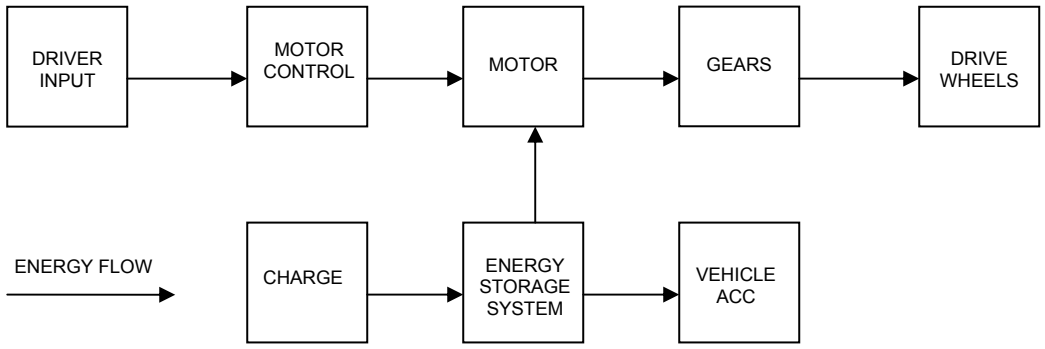

Figure 2.—Standard Carryall Block Diagram

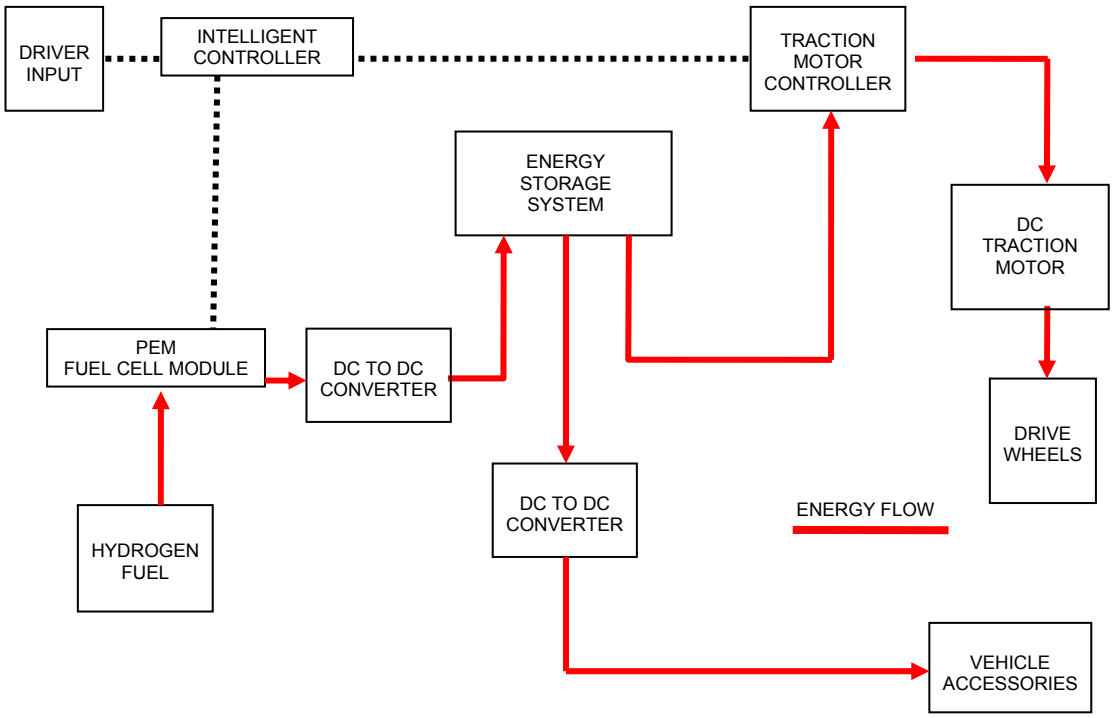

Figure 3.—Fuel Cell Powered Carryall Block Diagram

Figure 4.—Standard Carryall Battery Pack

There were several modifications made to the Carryall for the implementation of the fuel cell based power system. The standard lead acid batteries and battery charger were removed. Two series connected 1.2 kW Ballard Nexa PEM fuel cells were installed, along with a metal hydride hydrogen storage system. The Ballard Nexa power module is a small, low maintenance and fully automated fuel cell system designed to be integrated into products for portable and back-up power markets. It is ready to integrate into a variety of products for commercial use. The Nexa power module is shown in figure 5 and described in detail in appendix A. The Nexa system is based on a PEM hydrogen, air fuel cell. The system provides up to 1200 watts of unregulated DC power at a nominal output voltage of 26 VDC. With the use of an external fuel supply, operation is continuous, limited only by the amount of fuel storage. Water produced by the fuel cells is contained within the vehicle, rather than being dispersed. No external power is required to start or recharge the Carryall; all power is derived from the vehicle.

A fuel cell converts hydrogen and oxygen into water, and in the process, produces electricity. Air can be used as the source of oxygen. The PEM fuel cell selected for this application uses a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. PEM fuel cells operate at relatively low temperatures, approximately 80 °C (176 °F). Low temperature operation allows them to start quickly (less warm-up time) and results in improved reliability. By converting fuel directly into energy through an electrochemical reaction, fuel cells extract more power out of the same quantity of fuel when compared to traditional combustion, with efficiency up to 90 percent. PEM fuel cells operate at 80 °C, rather than 2,300 °C, as in an internal combustion engine. Fuel cells do not contain any moving parts, which allows for higher reliability and longer life. When hydrogen is the fuel; water, heat and electricity are the by-products of the electrochemical reaction in a fuel cell generating electricity, instead of carbon dioxide, nitrogen oxides, sulfur oxides and particulate matter inherent to fossil fuel combustion. Fuel cells avoid the environmental damage associated with the extraction of fossil fuels from the Earth when the hydrogen is produced from renewable sources. Fuel cells are capable of operating on hydrogen, or hydrogen reformed from any of the common fossil fuels. Hydrogen can be domestically produced through coal gasification, reformed from natural gas, or through the electrolysis of water with renewable sources such as photovoltaics or wind.

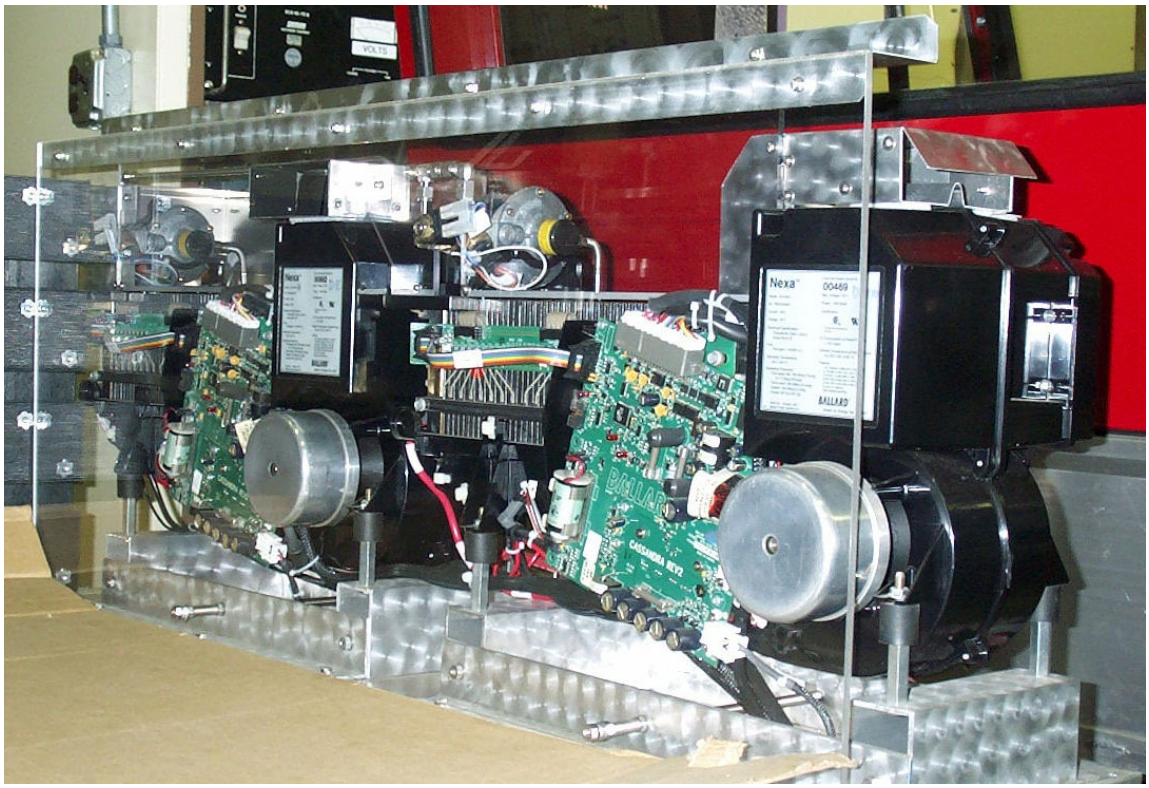

Figure 5.—Proton Exchange Membrane (PEM) Fuel Cells Installed in Carryall

Hydrogen is traditionally stored as a compressed gas or as a cryogenic liquid. Both of these storage methods have shortcomings that present problems for the use of hydrogen as a ubiquitous fuel gas. A metal hydride hydrogen storage system was selected for this application. Hydride hydrogen storage stores hydrogen in a low-pressure solid form.

In a metal hydride hydrogen storage system, metal alloys are used that act like sponges to absorb hydrogen. The absorption of gaseous hydrogen into the solid metal forms a new material called a metal hydride. In order for the absorption process to occur, heat needs to be removed during the reaction process. Heat also needs to be supplied during the desorption process. The source of the heat supplied can be waste heat from the fuel cell.

Metal hydrides are an extremely efficient method of storing hydrogen. It is twice as efficient as the next most efficient method of storing hydrogen, which is as a liquid. Hydrogen is stored safely at ambient temperatures and pressures. Metal hydrides are able to deliver very pure hydrogen. This is particularly important for PEM fuel cells, which use Pt catalysts that can be easily poisoned if certain impurities (such as CO) are present in the hydrogen. Metal hydrides have negligible, if any, loss during storage, giving them extremely long shelf. The metal hydrides can be used to absorb waste heat from the fuel cell.

A custom lightweight, efficient DC to DC converter converts the voltage from the series connected fuel cells, which can vary from 44 volts to 90 volts, to a regulated 50 volts for the traction power system. The DC to DC converter has input current limiting to protect the fuel cells. The DC to DC converter also has output overvoltage protection to protect the ultracapacitors and the vehicle traction power system. The Fuel Cell Powered Carryall control electronics are shown in figure 6 and described in detail in appendix A.

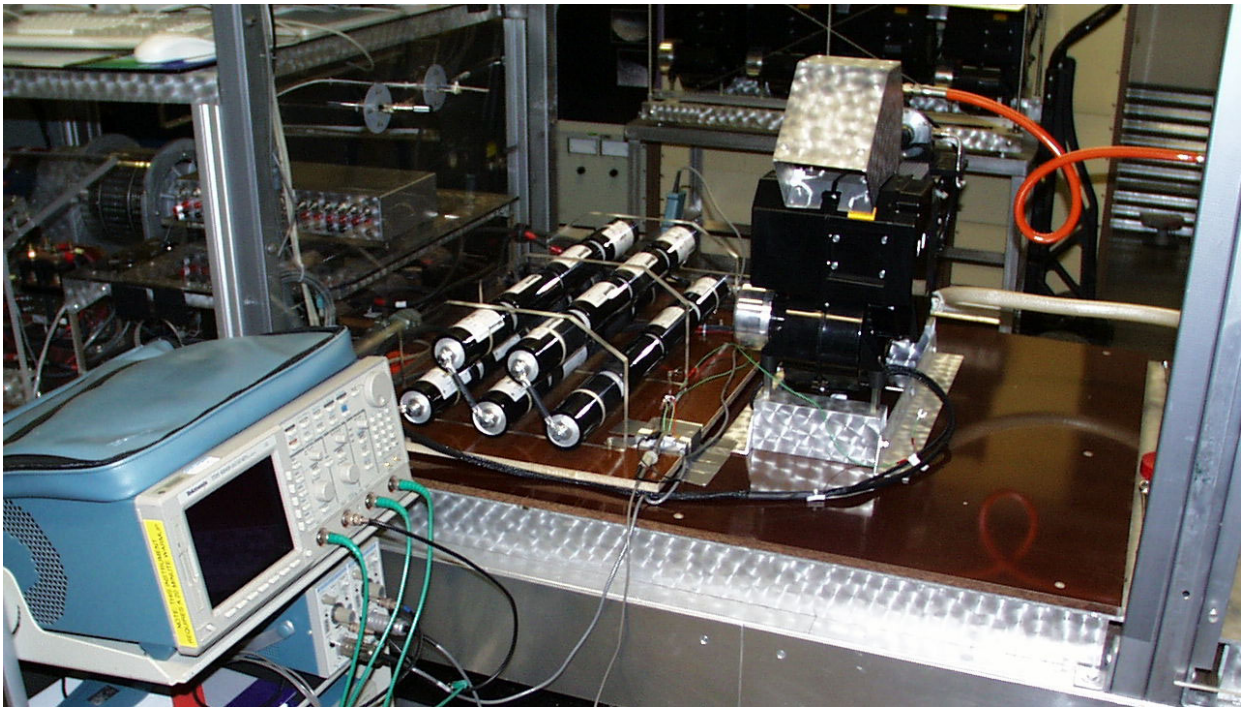

Figure 6.—Bank of 20 Series Connected Ultracapacitors

A symmetric ultracapacitor energy storage system was implemented for handling vehicle transient loads. The ultracapacitor bank consists of 20 series connected 2,600 Farad ultracapacitors for a total capacitance of 130 Farads. The energy rating of the energy storage system is 162.5 kJ. The ultracapacitors were interconnected directly through threaded rods, rather than through cables, to minimize interconnection losses and improve efficiency. The ultracapacitor bank is shown in figure 7 and described in detail in appendix A. This state-of-the-art technology not only has much longer life than conventional batteries, but also provides much higher current capacity than batteries. Ultracapacitors are maintenance free, and have excellent low temperature characteristics.

The electric traction motor is a 3.1 horsepower series wound unit. This is a direct drive system with double reduction helical gears. A pulse width modulated motor controller allows for efficient speed control over a wide speed range.

A 12 volt, spiral wound, valve regulated, deep discharge, maintenance free, lead acid battery is used for starting, lighting, and operating vehicle accessories. This is a state of the art lead acid battery. The battery is rated at 41 amp hours. The battery is charged from the fuel cells via a lightweight and efficient 200 watt battery charging module.

The instrument panel of the standard Carryall was modified to accommodate the controls required for operating the fuel cells. A 100 volt analog voltmeter was added to the instrument panel to indicate the voltage level of the two series connected fuel cells. Individual controls were provided for each of the fuel cells. Data ports were also provided for each of the fuel cells. A 15 volt analog voltmeter was added to indicate the voltage level of the 12 volt auxiliary battery. A master switch for the 12 volt auxiliary battery was also added. An electronic speedometer with trip odometer was installed. All of the standard Carryall controls were retained. The instrument panel is shown in figure 8.

The vehicle incorporates Department of Transportation specified safety features including lights, mirror, and horn.

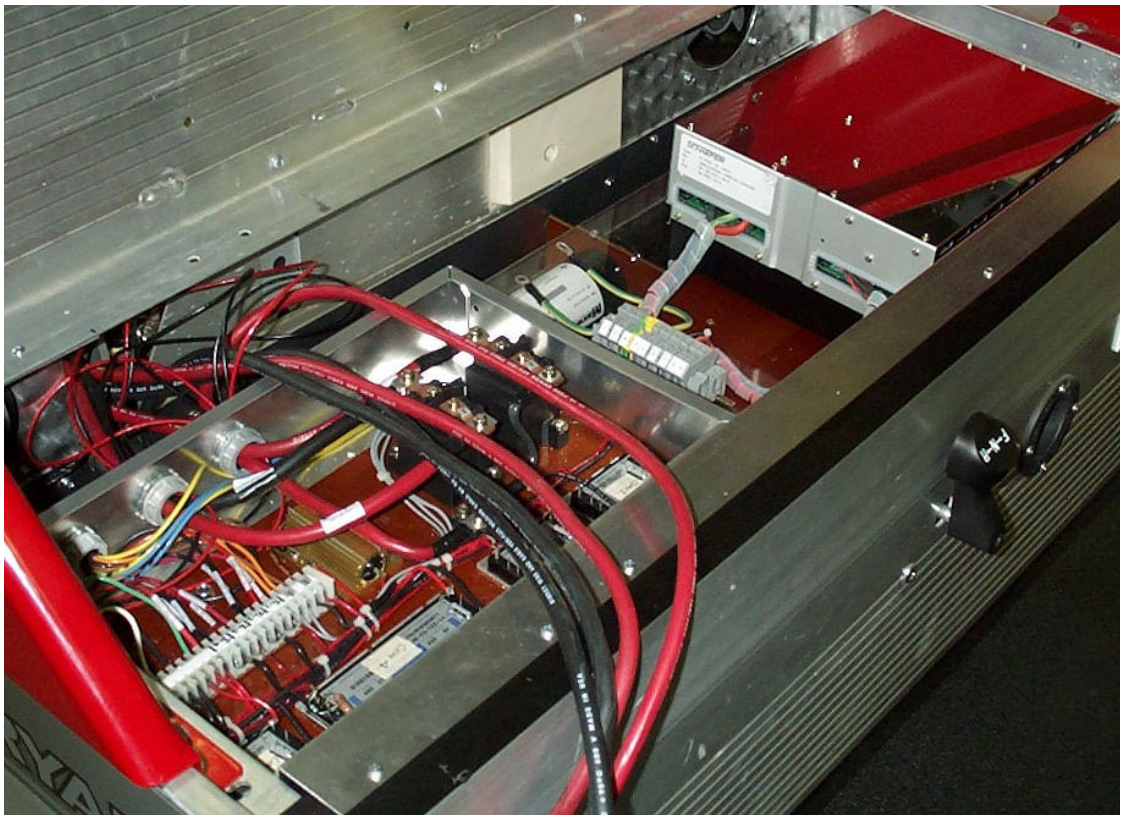

Figure 7.—Fuel Cell Powered Carryall Control Electronics

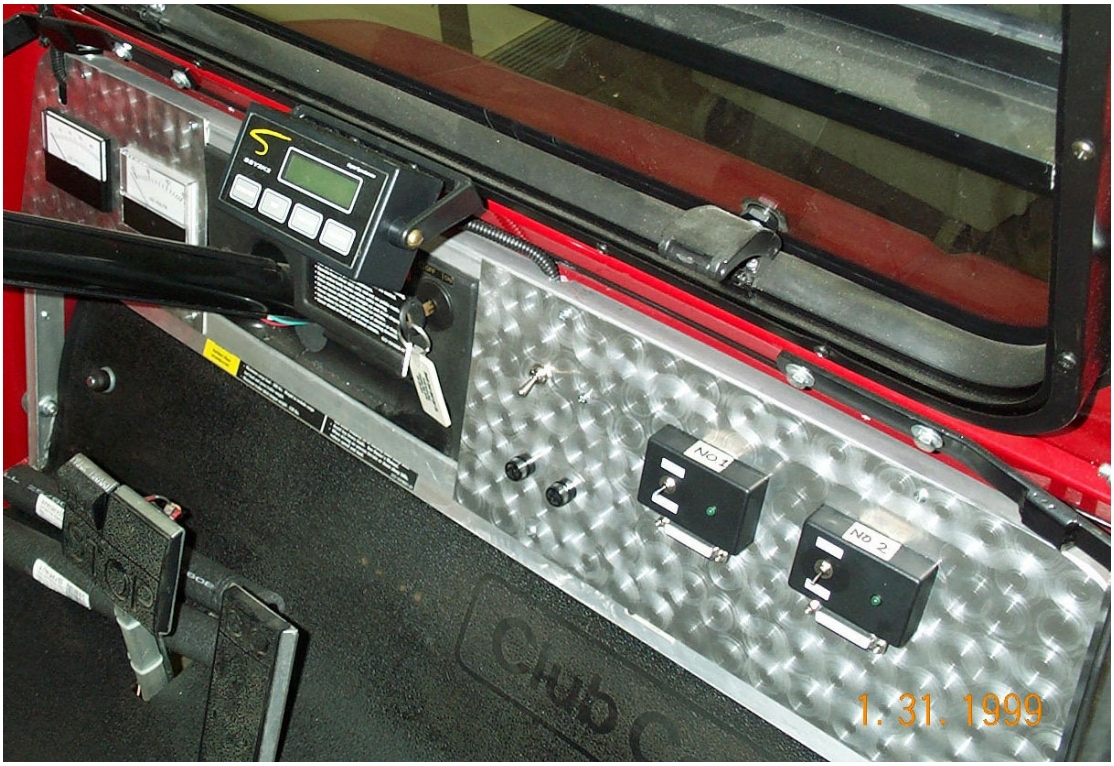

Figure 8.—Fuel Cell Powered Carryall Instrument Panel

Instrumentation

The Carryall was instrumented to measure vehicle speed and distance. The fuel cells include data ports which are sampled and stored on a laptop PC. Additional channels will measure the traction voltage and current, as well as the following temperatures: traction motor, motor controller, energy storage, and the ambient temperature. These data will be sent to an on-board digital data acquisition system and stored on a laptop PC. Power for the data acquisition system, will be derived from a portable power system. The instrumentation configuration is described in appendix B.

Performance

The standard Carryall with lead acid batteries had been tested previously and the results are tabulated in the NASA TM of reference 1. The PEM fuel cells in conjunction with ultracapacitors had been tested previously, and the results are tabulated in the NASA TM of reference 2. The hydride hydrogen storage system has been tested as an individual component, and has been integrated into the vehicle.

Concluding Remarks

The Club Car Carryall with the standard battery pack is a commercially available vehicle that is fully prepared for the mass market. The Carryall has also been tested very successfully with asymmetric ultracapacitor energy storage. The primary focus of this report is the development of the fuel cell powered Carryall. The vehicle is powered completely from fuel cells, and does not require any external power source for starting or operation.

There are many unique aspects of the vehicle. Hydrogen powered PEM fuel cells are the primary power source. PEM fuel cells have a rather fragile membrane with limited life. The life is significantly reduced by high stresses produced by large transient loads. The load must be minimized to prevent fuel cell damage, or an energy storage system is strongly encouraged if high peak loads exist. Ultracapacitors can easily handle large transient loads on a continual basis, and still provide a very long life, as no chemical reactions are occurring. Ultracapacitor charging is significantly more efficient than battery charging, since there is no chemical reaction occurring. Ultracapacitors are capable of supplying very high power, which is required to accelerate the vehicle quickly. Ultracapacitors are ideal for applications such as electric vehicles where long life, maintenance free operation, and excellent low temperature performance is essential. The combination of PEM fuel cells and ultracapacitors provides a power source with excellent energy and power density.

Another unique aspect of the project is the use of metal hydride hydrogen storage. Hydrogen is traditionally stored as a compressed gas or as a cryogenic liquid. Both of these storage methods have shortcomings that present problems for the use of hydrogen as a ubiquitous fuel gas. Hydride hydrogen storage stores hydrogen in a safe and efficient low-pressure solid form.

Future plans for the Carryall includes the testing of the vehicle with regenerative braking. Ultracapacitors will be used for regenerative braking, because of their superiority to batteries in accepting high braking currents, allowing for less usage of the mechanical brakes.

The Club Car Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future aeronautic and space applications.

References

1. Eichenberg, D.J., “Baseline Testing of the Club Car Carryall With Asymmetric Ultracapacitors,” NASA/TM—2003-212705, November 2003.
2. Eichenberg, D.J., “Baseline Testing of Ultracapacitors for the Next Generation Launch Technology (NGLT) Project,” NASA/TM—2004-213344/REV1, February 2005.

Appendix A—Vehicle Summary Data Sheet

1.0	Vehicle Manufacturer	Club Car Inc. Augusta, Georgia
2.0	Vehicle	Carryall 1
3.0	Vehicle Configuration	Series Electric
4.0	Traction Motor	
4.1	Traction Motor Configuration	Series Wound DC
4.2	Traction Motor Power	3.1 horsepower
4.3	Traction Motor Cooling	Air cooled
5.0	Drivetrain	
5.1	Traction Motor Drivetrain	Direct Drive, Double Reduction Helical Gears
6.0	Vehicle Dimensions	
6.1	Wheel Base	65.5 in. (166.4 cm)
6.2	Overall Length	103.5 in. (262.9 cm)
6.3	Overall Width	48 in. (121.9 cm)
6.4	Overall Height	48 in. (121.9 cm)
6.5	Ground Clearance	4.5 in. (11.4 cm)
6.6	Front Tread	34.5 in. (87.6 cm)
6.7	Rear Tread	38.5 in. (97.8 cm)
6.8	Cargo Bed Load Size	37.6 in. (95.6 cm) x 45.1 in. (114.6 cm) x 9.3 in. (23.5 cm)
6.9	Cargo Bed Load Height	27.5 in. (69.9 cm)
6.10	Cargo Bed Load Capacity	300 lb. (272.4 kg)
6.11	Vehicle Load Capacity	800 lb. (363.2 kg)
6.12	Standard Dry Weight	530 lb. (240.6 kg)
6.13	Outside Clearance Circle	17.5 ft (5.3 m) dia.
6.14	Turning Radius	8.4 ft (2.6 m)
6.15	Intersecting Aisle Radius	72 in. (182.9 cm)
7.0	Ballard Nexa Proton Exchange Membrane (PEM) Fuel Cell Power Module	
7.1	Rated Net Power	1200 W
7.2	Rated Current	46 A
7.3	DC Voltage Range	22 to 50 V
7.4	Operating Lifetime	500 h
7.5	Fuel Composition	99.99% dry gaseous hydrogen
7.6	Fuel Supply pressure	10 to 250 psig (69 to 1724 kPA)
7.7	Fuel Consumption	≤ 18.5 SLPM
7.8	Operating Ambient temperature	3 to 30 °C (37 to 86 °F)
7.9	Relative Humidity	0 to 95%
7.10	Location	Indoors and outdoors
7.11	Length x Width x Height	56 x 25 x 33 cm (22 x 10 x 13 in.)
7.12	Weight	13 kg (29 lb)
7.13	Certification	CSA, UL
7.14	Liquid Water Emissions	≤ 0.87 liters (30 fluid oz.) per hour
7.15	Noise Emissions	≤ 72 dBA @ 1 m
7.16	Fuel Interface	45° flared fitting for ¼-in. OD tube
7.17	Electrical Power Interface	#8 AWG electrical wire
7.18	Control Interface	Full duplex RS 485

8.0 Maxwell BCAP0010 Ultracapacitor

8.1	Configuration	Symmetric, dual layer
8.2	Capacitance	2600 F
8.3	Energy Rating	8.125 kJ
8.4	Voltage Rating	2.5 V continuous, 2.8 V peak
8.5	Maximum Series Resistance	0.7 milliohms
8.6	Specific Power Density	4.3 kW/kg
8.7	Maximum Current	600 A
8.8	Leakage Current	5 mA
8.9	Operating Temperature	–40 to 65 °C (–40 to 149 °F)
8.10	Storage Temperature	–40 to 70 °C (–40 to 158 °F)
8.11	Dimensions	60 x 172 mm (2.36 x 6.77 in.)
8.12	Weight	525 g (1.16 lb)
8.13	Volume	0.42 L (23.63 cubic in.)

9.0 Ultracapacitor Bank (Maxwell BCAP0010)

9.1	Configuration	20 series ultracapacitors
9.2	Capacitance	130 F
9.3	Energy Rating	162.5 kJ
9.4	Voltage Rating	50 V continuous, 56 V peak
9.5	Maximum Series Resistance	14 milliohms
9.6	Weight	10.5 kg (23.15 lb)
9.7	Volume	8.4 L (512.60 cubic in.)

10.0 Traction System DC/DC Converter (Schaefer C 4749-W-U010E)

10.1	Input Voltage Range	44 to 90 V
10.2	No-Load Input Power	10 W
10.3	Output Voltage	50 V
10.4	Output Current	42 A
10.5	Line Regulation	0.1%
10.6	Load Regulation	0.2%
10.7	Output Ripple	≤1%
10.8	Load Transient (10-90-10%)	6%
10.9	Response Time (±1%)	2 ms
10.10	Turn-On Rise Time	2 s
10.11	Overload Protection	Current limited to 105% full load
10.12	Overvoltage Protection	55 V
10.13	Operating Temperature	–20 to 75 °C (–4 to 167 °F)
10.14	Storage Temperature	–40 to 85 °C (–40 to 185 °F)
10.15	Cooling	Natural convection
10.16	Efficiency at Full Load	80%
10.17	Switching Frequency	20 kHz
10.18	Isolation Resistance	≥ 10 megohms at 500 V

11.0 Metal Hydride Hydrogen Storage Canister (Texaco Ovonic Model No. 85G250B-NPT)

11.1	Dimensions	8.9 cm OD, 38.3 cm long (3.5 in. OD, 15.06 in. long)
11.2	Weight	6.5 kg (14 lb)
11.3	Hydrogen Capacity	80 g, 900 std. Liters
11.4	Maximum Internal Pressure	250 psi at 25 °C
11.5	Container	1800 psi DOT 3-AL cylinder
11.6	Connection	1/8 in. FNPT with manual shut-off
11.7	Safety Devices	Thermal/pressure relief certified to CGA S-1.1 (CG-7 and CG-10)
11.8	Operating Temperature	0 to 75 °C (32 to 167 °F)
11.9	Storage Temperature	–29 to 54 °C (–20 to 130 °F)

12.0 Auxiliary Battery (Optima Model No. 51)

12.1	Voltage	12 V
12.2	Energy	41 Amp hours
12.3	Reserve	70 minutes
12.4	Dimensions (L x W x H)	9.25 x 5.0 x 9.0 in.
12.5	Weight	26.0 lb

Appendix B—Description of the Instrumentation System

A block diagram of the instrumentation system is shown in figure B-1.

All fuel cell data will be obtained by the fuel cell instrumentation system and transmitted to a personal computer (PC) via a serial interface. The PC will log the data. This data included the fuel cell voltage, the fuel cell current, and the fuel cell temperature. All other measurements will be obtained with a Hewlett Packard data acquisition system, sampling at 100 Hz. Type K thermocouples will be used for all temperature measurements. Hall effect transducers will be used for all current measurements. Speed and distance will be monitored by a proximity sensor. These data will be transmitted to a laptop PC via a serial interface. The PC will log the data.

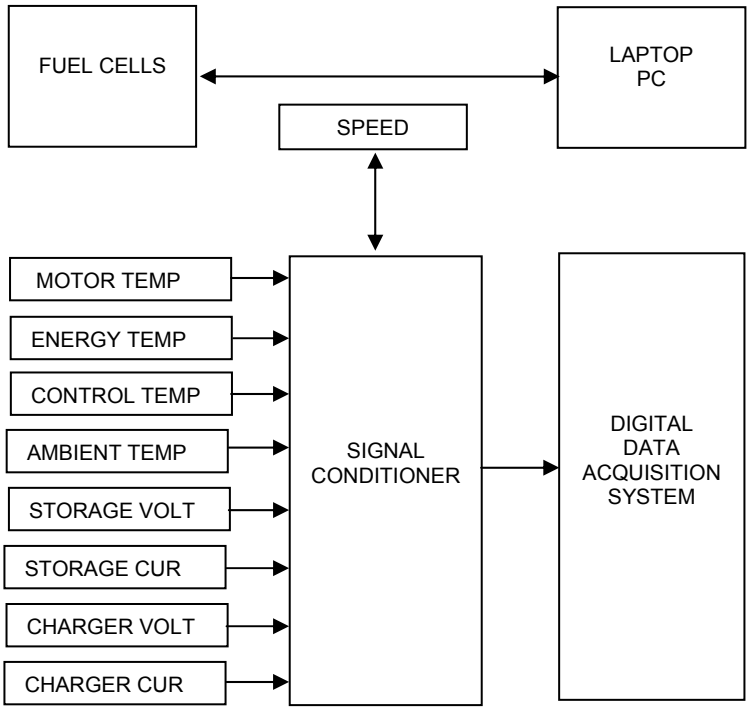

Figure B-1.—Vehicle Instrumentation System

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13. ABSTRACT ***(Maximum 200 words)***
The NASA Glenn Research Center initiated development of the Fuel Cell Powered Club Car Carryall as a way to reduce pollution in industrial settings, reduce fossil fuel consumption and reduce operating costs for transportation systems. The Club Car Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future aeronautics and space applications. The work was done under the Hybrid Power Management (HPM) Program. The Carryall is a state of the art, dedicated, electric utility vehicle. Hydrogen powered proton exchange membrane (PEM) fuel cells are the primary power source. Ultracapacitors were used for energy storage as long life, maintenance free operation, and excellent low temperature performance is essential. Metal hydride hydrogen storage was used to store hydrogen in a safe and efficient low-pressure solid form. The report concludes that the Fuel Cell Powered Club Car Carryall can provide excellent performance, and that the implementation of fuel cells in conjunction with ultracapacitors in the power system can provide significant reliability and performance improvements.

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