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"Report on specification and features of the fuel cell busses"

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“Report on specification and features of the fuel cell busses”

1 Introduction

One of the goals of the ECTOS program is to collect as much field experience as possible with the fuel cell technology. Experiences from the NEBUS, the first Mercedes-Benz fuel cell bus, have shown that it was not necessarily the fuel cell itself which was decisive for vehicle availability but in fact the various auxiliary units. Special attention was therefore given to maximising the use of standard series components from the start of the development phase of the Fuel Cell Citaro in order to achieve a high availability of the entire drive train.

For this reason it was decided to develop the fuel cell drive train based on the conventional Mercedes-Benz Citaro, employing, besides the main components such as alternators, compressors etc., also the standard automatic transmission, while being aware that this might have negative effects on the vehicles fuel economy.

2 The Fuel Cell Citaro

The Fuel Cell Citaro is based on the 12 meters series vehicle of EvoBus which features a standing platform in the left rear area for placing a standing engine as well a an automatic transmission. The body shell work of these vehicles was reinforced especially in the area of the roof due to the three tons of extra load for the fuel cell drive train and the air conditioning system. The suspension has been adapted to accommodate the higher weight and the increased tendency to roll.

No modifications to the entirely low floor construction and the door concept were necessary. Also the outside dimensions remained unchanged except for the vehicle height which increased to approx. 3,70 m due to the fuel cell drive train and the fans of the cooling module. The technical data in the table describe the vehicle comprehensively.

Table1: ***Characteristics of the Fuel Cell Citaro***

Overall length / mm	11,950
Overall width / mm	2,550
Overall height / mm	3,688
Min. turning Diameter / mm	21,542
Curb weight / kg	~14,000
Gross weight /kg	standard: 18,000 with special permit : 19,000
Max. front axle load /kg	7,245
Max. rear axle load /kg	12,000
Passenger seat number	~30 depending on customer requirements
Max. passenger number	< 70 @18t gross weight >70 @19t gross weight

3 The Fuel Cell Drive Train

General Description

The HY-205 P5-1 engine is the fifth generation of heavy-duty drive trains developed in Ballard, Vancouver (Canada). It was designed around the newest Mk9 stack technology to efficiently convert gaseous hydrogen fuel and atmospheric oxygen directly into electricity and water. The electricity is fed to a compact but powerful liquid cooled electric motor, which provides the bus traction and also drives the fuel cell engine auxiliaries and the bus auxiliaries through a central gear case.

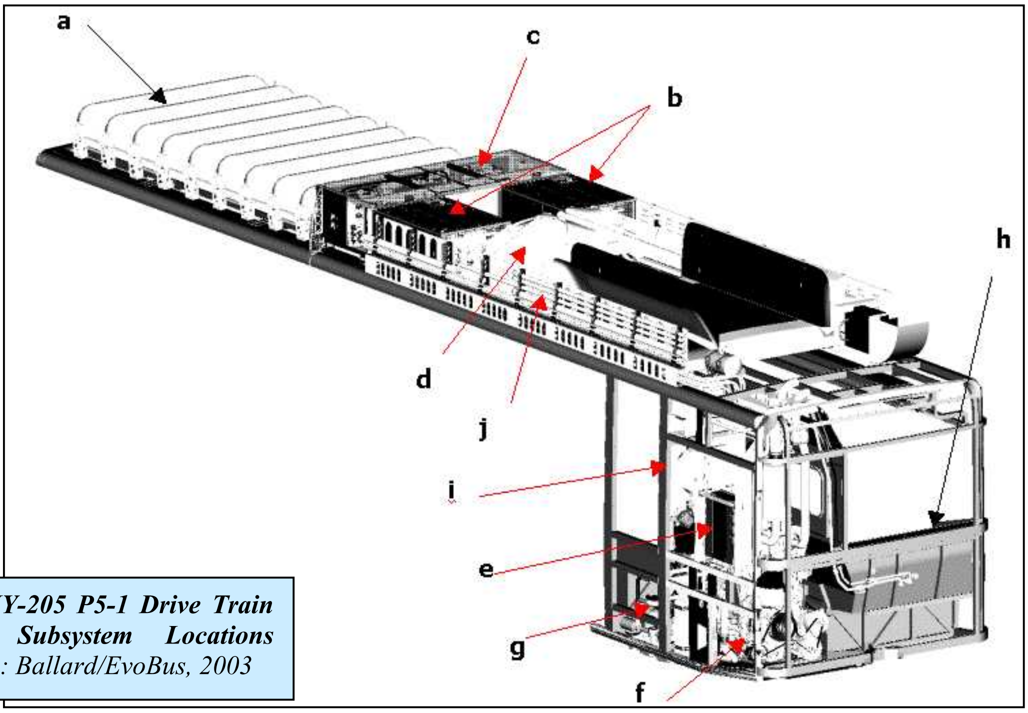
The P5-1 fuel cell engine design and architecture focuses on reliability and durability by using as much as possible industrial available auxiliaries. The drive train arrangement in the vehicle addresses as much as possible European safety regulations and standards.

It is designed to enable a direct replacement of a diesel drive train commonly used in bus applications. The electric motor module has conventional motor mounts and an industry standard, SAE 1 transmission flange. It can be mated to any suitable automatic transmission and differential to provide a reliable vehicle traction system with excellent hill climbing ability, fast acceleration and high road speed. The electric motor operates continuously from an idle speed of about 600 rpm to a maximum speed of about 2100 rpm.

The HY-205 fuel cell drive comprises the following main systems and functional groups (cf. figure):

a) Hydrogen fuel storage system incorporating 350 bar hydrogen pressure vessels with a total capacity of about 40-42 kg.
b) Fuel cell modules (2)
c) Interface module and piping system
d) Radiators for heat transfer
e) Inverter for converting DC into 3 phase alternating current
f) Auxiliary gear case and electric drive
g) Automatic torque converter
h) Fuel cell control device
i) Air supply system
j) Cooling System

These modules are integrated packages, with defined fluid, electrical and mounting interfaces. The modules are connected to each other, and to the bus, with interconnection piping and interconnection power wiring systems. In addition to the main systems, the hydraulic pump circuit and lubrication oil circuit are powered by the auxiliary gear case. The 24V DC supply is provided by three belt driven alternators which are also driven by the auxiliary gear case.



The HY-205 P5-1 Drive Train Main Subsystem Locations
Source: Ballard/EvoBus, 2003

Functional Description of the Fuel Cell Drive Train

Start-Up

The fuel cell drive is started in the same way as normal diesel drive trains with the coach ignition key. Upon completion of the controller test cycle, the starter puts the electrical motor into idle speed and the main hydrogen shut-off valve opens. At the same time the air compressor, which is connected to the auxiliary gear case, initiates the airflow to the cathode side of the fuel cell stacks.

The hydrogen pressure regulator, which maintains the hydrogen pressure slightly above the air pressure, starts and is followed by the anode hydrogen flow of the fuel cell. As soon as the hydrogen and the oxygen from the air reach the reaction surface of the fuel cell membrane, the electrical voltage starts to build up. The inverter is switched on as soon as minimum necessary operational voltage of the motor / inverter is reached. The starter is disconnected after the operational condition has stabilised.

Driving

When the driver actuates the throttle pedal, the angle position of the pedal is converted by the controller into a torque request signal (drive controller). The torque request is then converted into direct current (DC). The supplied DC level depends on the airflow available to the fuel cell. The airflow increases proportionally with the current demand. Accordingly the airflow is the key mechanism for a load change.

The hydrogen flow is not actively controlled. Instead the hydrogen pressure tracks the fuel cell air pressure. This is accomplished through a pressure regulator that has been custom designed for this application. To obtain a fast air flow response and to achieve the correct fuel stoichiometry, the airflow must be tightly controlled. For this a control mechanism is required that controls the airflow independently from the motor speed and drive speed. The air diverter valve provides the independent control of the airflow from the motor speed. Through this valve the required airflow for the fuel cell operation can be controlled partially independently from the speed of the air compressor.
During the run-up procedure the torque request or current request is converted into the airflow that corresponds to the operational condition.

During the turndown procedure the motor continues to run in controlled mode relative to the brake function and the torque that is required for driving the associated auxiliary drives.

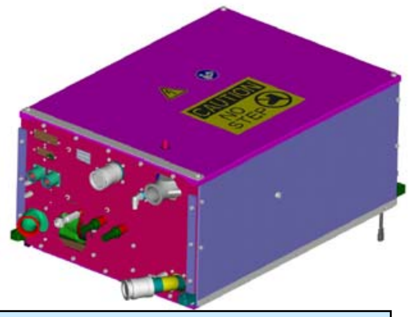
If no current is demanded from the fuel cell, the reaction gases (hydrogen and oxygen) are not consumed and remain in the fuel cell until another load change is requested.

Shut Down Procedure
The fuel cell drive is shut down either by driver control (e.g. the ignition key is placed into shut down position) or with the emergency shutdown circuit breaker. During the shutdown procedure the shut down valves on each storage tank are closed respectively. At the same time the main electrical breaker opens and the remaining hydrogen in the fuel cell is discharged over the ‘Purge Diffuser’ into the atmosphere.

The motor stops turning and the hydrogen pressure is reduced to the level of atmospheric pressure. All electrical systems of the fuel cell drive are disconnected. The 24V-DC of the on board system remains connected. The fuel cell is then in safe shutdown mode.

The Fuel Cell Stack Module

These fuel cell modules contain the fuel cell stacks, consisting of 6 discrete cell rows attached to a manifold plate. On the one side the cell rows are attached, on the opposite side reactant-conditioning system is attached.
The stack contains a module, which is the air and hydrogen humidifier, their associated hardware, the fuel cell hydrogen regulating and re-circulation system hardware, and the electronic cell voltage monitoring system.

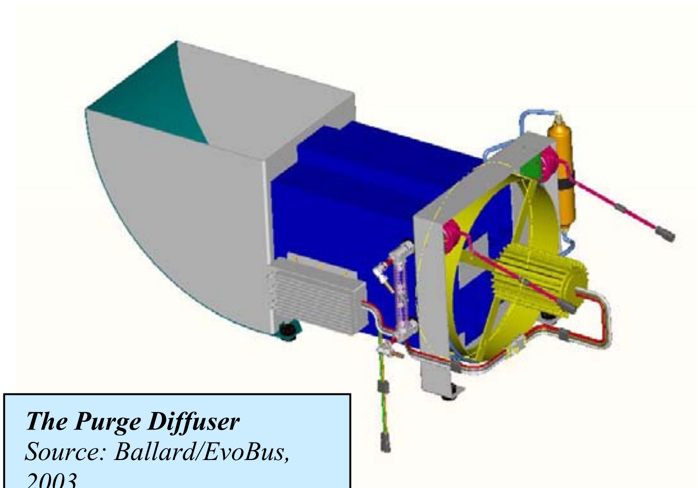


The Fuel Cell Stack Module
Source: Ballard/EvoBus, 2003

The stack modules are fully enclosed to prevent contamination and thermal impact. It is ventilated with a filtered air stream. The modules can be removed as a complete unit for servicing. For this application the two stack modules are located on top, and in the middle, of the roof, mounted with a special mounting bracket.

Discharging of Hydrogen into the Atmosphere ('Purging')

Due to hydrogen fuel contamination and to condensation that can result in water droplet formation on the anode side, it is necessary to purge the hydrogen circuit at certain intervals. The hydrogen gas, which contains the contaminants and the water vapour, is discharged through the "Purge Diffuser" into the atmosphere. The "Purge Diffuser" has been designed to provide safe disposal of the hydrogen into the atmosphere.

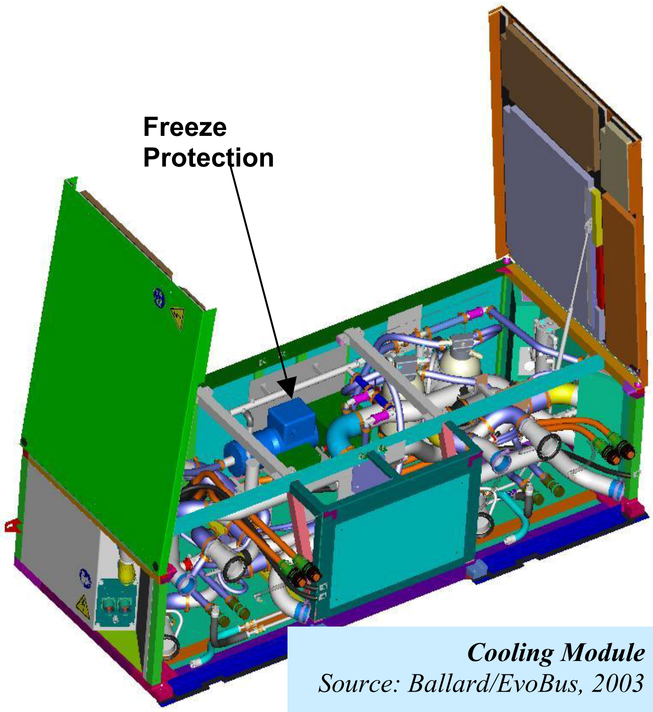


The Purge Diffuser
Source: Ballard/EvoBus, 2003

The hydrogen system must be purged on start-up, periodically during operation, and on shutdown, venting a small quantity of moist hydrogen and impurities to the atmosphere. The hydrogen diffuser module mixes the small volume of vented hydrogen with a large quantity of air, diluting the hydrogen mixture to a safe level. The hydrogen diffuser module is mounted on the roof of the bus, in a well-ventilated location. Under no circumstances the system will release hydrogen concentrations higher than 25% of the lower explosion limit.

Cooling System

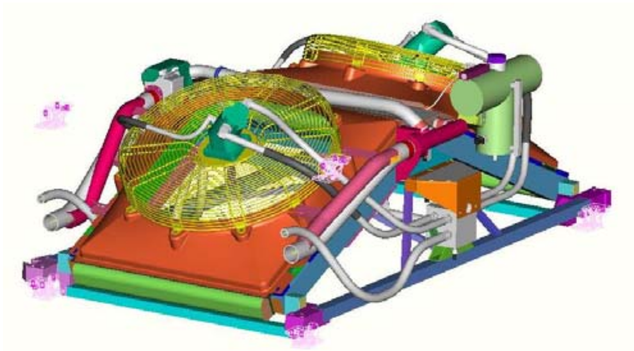
The Fuel Cell Process produces waste heat that must be removed from the fuel cell modules to sustain the proper operating conditions. The cooling circuit is provided with a special de-ionised (DI) water/ethylene glycol mixture that is non-conductive. Two coolant diverter valves control the correct cooling flow and the correct coolant inlet temperature at the fuel cell. The control is independent from the inlet temperature and the outlet temperature of the fuel cell.



Cooling Module
Source: Ballard/EvoBus, 2003

The heat of the fuel cell module is discharged to the atmosphere via a heat exchanger and two hydraulically driven fans. The heat exchangers of the drive train, the coach cabin and the transmission retarder are also connected to this cooling system.

The fan/radiator module(s) include the radiator(s), airflow ducting, and the hydraulically driven motor fan(s) and the hydraulic control valves and plumbing. A hydraulic pump driven by the electric motor provides power for the fan motor(s).



Roof Fans
Source: Ballard/EvoBus, 2003

The Water/Glycol Cooling System Module

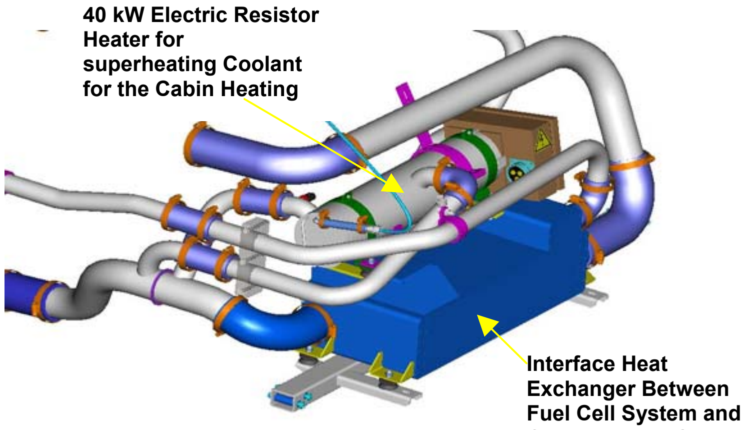
The fuel cell stacks are cooled by a special coolant fluid, made from pure de-ionised water and pure ethylene glycol. The DI-water/glycol cooling system includes a reservoir, a control valve, a de-ionising filter, a freeze protection system and various control valves. The DI-water/glycol cooling system only uses approved materials to prevent contamination of the coolant fluid. The DI-water/glycol passes through a radiator main heat exchanger and transfers the fuel cell waste heat to the atmosphere via the radiator-fan package.

The hardware described above is packaged in a selfcontained module, which interfaces via fluid ports with the Fuel Cell Stack Modules and the water/glycol system, mounted in various locations in the bus.

The water/glycol system also cools the inverter/controller, the electric traction motor cooling oil, and the automatic transmission retarder. This circuit also provides heat to the bus cabin heating system. The second water/glycol circuit is designed to allow the use of standard cooling systems materials and heat exchangers commonly used in the cabin heating area of a standard bus application.

Cabin Heating and Interface

The HY-205 engine provides a cabinheating interface to the coach. The system is based on an electric immersed heating device with an approximate heating power of 40 kW at full load. In order to provide cabin heat the fuel cell engine has to be active.



Cabin Heater Module
Source: Ballard/EvoBus, 2003

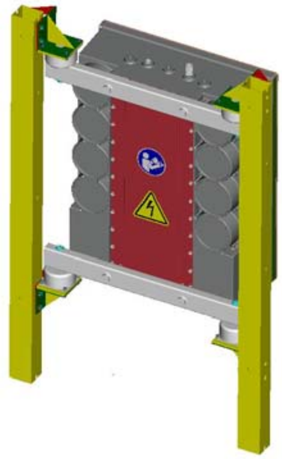
The Citaro bus application has the dump resistor housing situated in the engine bay located in the same place where the cabin heating system for a diesel bus used to be. The cabin heating circulation pump, as well as the temperature control software and algorithms are OEM specific. Additional piping is required to connect the roof package to the bus cabin heating system.

Cold Start and Freezing

The stack modules are equipped with thermal insulation in order to extend the cool down time periods. In order to realise quick start capability the fuel cell system should be kept above +5°C. This will be managed via an electrical block heater, which operates from an external energy source and a small circulation pump. The block heater is thermostat controlled. The fuel cell engine can be off.

The Inverter/Controller Module

The inverter/controller module converts the raw DC electrical power produced by the fuel cell stacks into controlled AC power for the electric motor. This module is cooled via the normal water/glycol circuit.



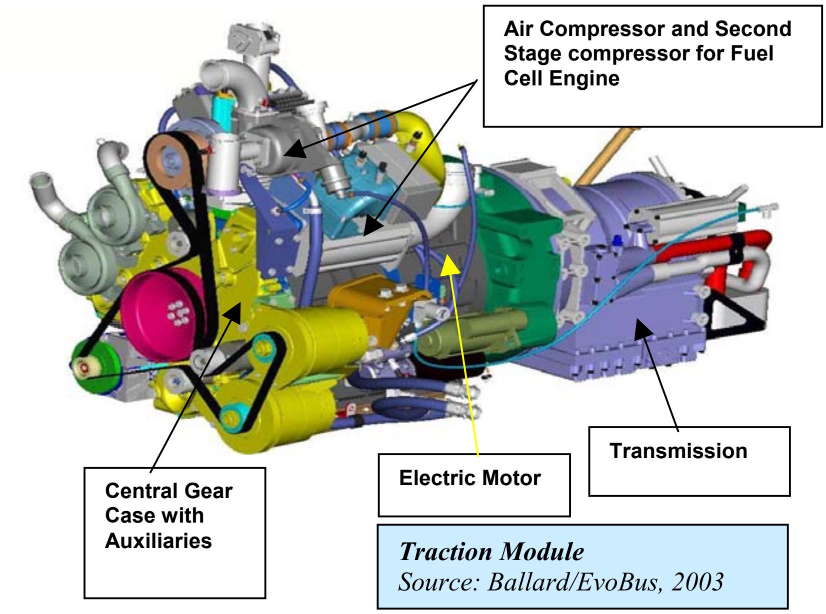
Inverter Module
Source: Ballard/EvoBus, 2003

Table 2: ***Traction Module Output Characteristics***

General Output Specifications		
Nominal Motor Output	250 kW shaft power	
Capacity	340 kVA	
Rated Output Current	450 A (1200 VDC IGBT)	
Maximum Output Voltage	3-phase, 460 V **OR** 0.7 x DC input voltage – whichever is less	
Rated Output Frequency	400 Hz (maximum) at full torque	
Overload Capacity	150% Rated Current / 1 minute	
PWM Frequency	Minimum 2.5 kHz Maximum 5 kHz	
Control Power Supply		
Voltage Range	14-35 V	
Load Rating	Inverter	6A (maximum)
Main Power Supply		
Input Current	425 A continuous, 540 A maximum for 5 minutes	
Rated Voltage	600 VDC (full load) to 900 VDC (zero load) input.	

The Auxiliary Drive & Electric Motor/Traction Module

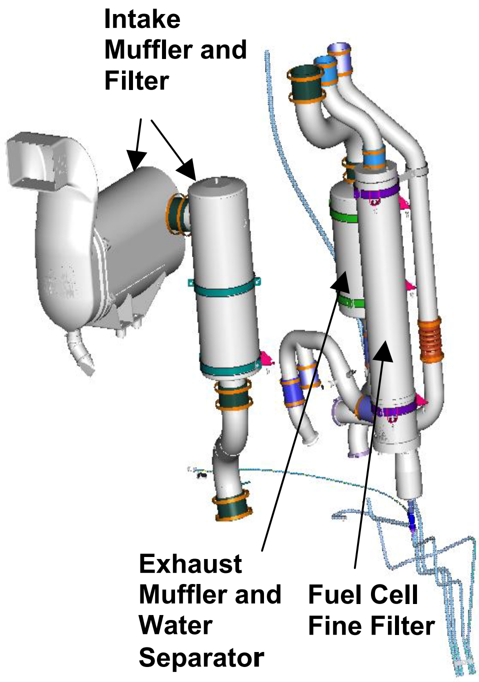
A front-end gear case, the alternator and air conditioning compressor drive standard bus auxiliaries such as the air brake compressor, power steering pump, and the radiator fan pump, by a belt drive. The gear case also activates the fuel cell engine auxiliaries including the supercharger and two water/glycol pumps. The auxiliary drive module is operated by a single electric motor. The same motor also powers a standard automatic transmission through an SAE 1 transmission flange to provide bus traction. A standard hydraulic retarder, part of the transmission, provides supplementary braking.



Traction Module
Source: Ballard/EvoBus, 2003

The Fuel Cell Air System

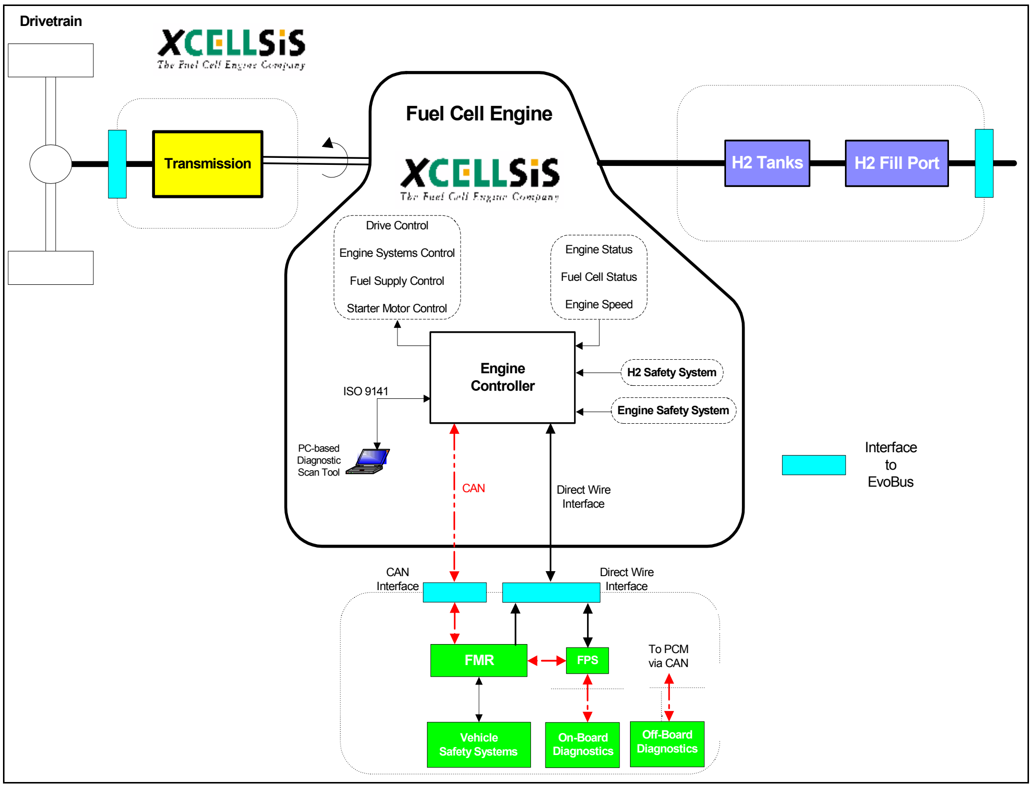
A supercharger, driven by the electric motor, produces pressurised air, which is supplied to the fuel cell stacks. After leaving the stacks the pressurised air is exhausted through a turbocharger, which recovers energy from the exhaust and provides a second stage of air compression. The air supply system also includes an inter-cooler to improve compression efficiency and an air filter to remove contaminants. Mufflers on the air system intake and exhaust quieten the supercharger and the turbocharger in order to meet the noise requirements of the overall vehicles.



Fuel Cell Air System
Source: Ballard/EvoBus, 2003

Electronic Interfaces to the Bus

The control interface between the bus and the engine is an industry standard digital format. The main control interface between the bus and the engine is realised via an industry standard fault-tolerant communication protocol (CAN, or Controller Area Network).
A set of discrete signals between the bus and the engine controller are interfaced via automotive relays. The engine controller and associated sensors and control devices require a 12 VDC supply, provided from one 12 VDC battery through the use of an equaliser.

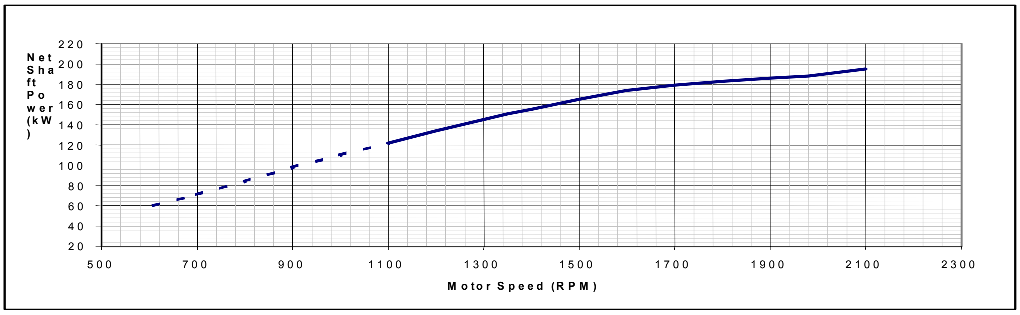


Electronic Interfaces
Source: Ballard 2003

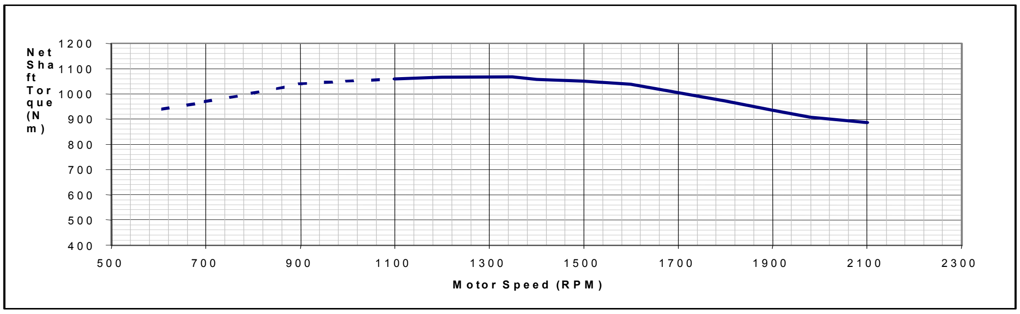
Table 3 ***Fuel Cell Engine Specifications***

Emissions	CO NO_X HC SO_2 Particulates CO_2	0.000 0.000 0.000 0.000 0.000 0.000
Performance	Net Shaft Power Peak torque	190 kW @ 2100 RPM 1050 Nm @ 800 RPM
Fuel	Gaseous hydrogen at ambient temperature Supply pressure (min) required Flow (max)	 100 bar 0.005 kg/s
	Fuel purity	BPS 136-0454-CA
Onboard Fuel Storage	CGH_2 Capacity @ 350 bar	<40 kg
Air	Two stage compressor Flow rate (max)	 0.3 kg/s
Cooling System	Water/glycol cooling loop with coach heating Interface	
Temperature	Fuel cell operating Ambient operating Ambient Storage without freeze provision Ambient Storage with freeze provision	70°C to 80°C -20°C to 40°C 2°C to 50°C -20°C to 40°C
Pressure	System operating (nominal)	20 bar
Electric Power	Fuel Cell Voltage Range Liquid cooled IGBT Inverter Integral Ground Fault Detection	550 to 900 VDC
Engine Control System	Power train control module: 32 bit 24 MHz power PC microcontroller, 1 CAN channel for customer interface CAN Converter Module 15011898 to 15011992	
Dynamic Braking	Supplied by transmission retarder	
Transmission	SAE 1 transmission flange	

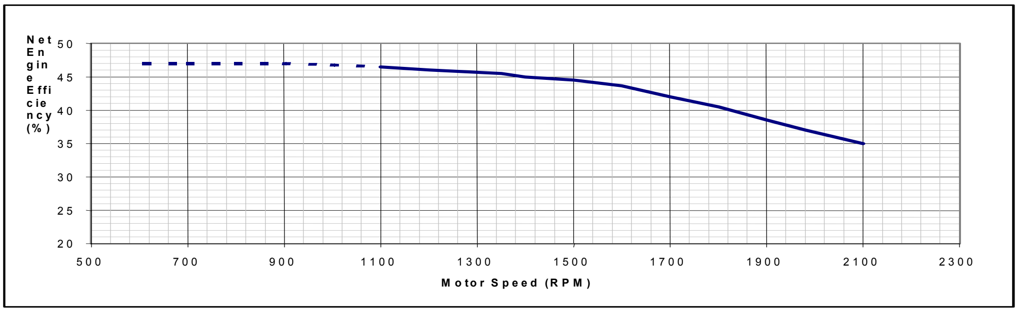
OUTPUT POWER to the Transmission Interface

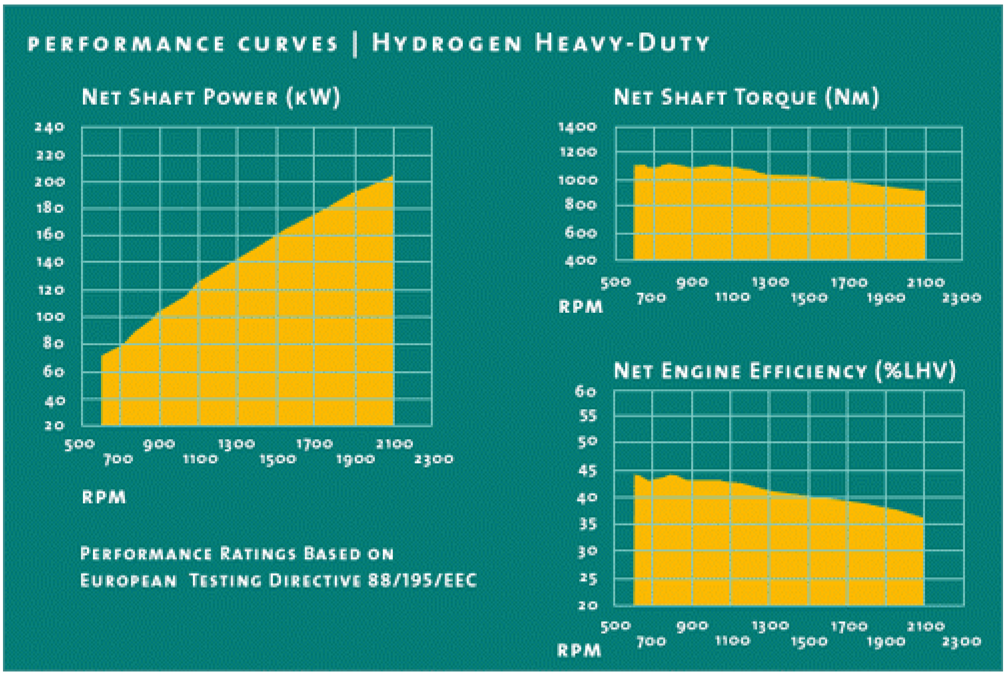


OUTPUT TORQUE to the Transmission Interface



HY-205 P5-1 Efficiency Curve Based on Lower Heating Value of Hydrogen

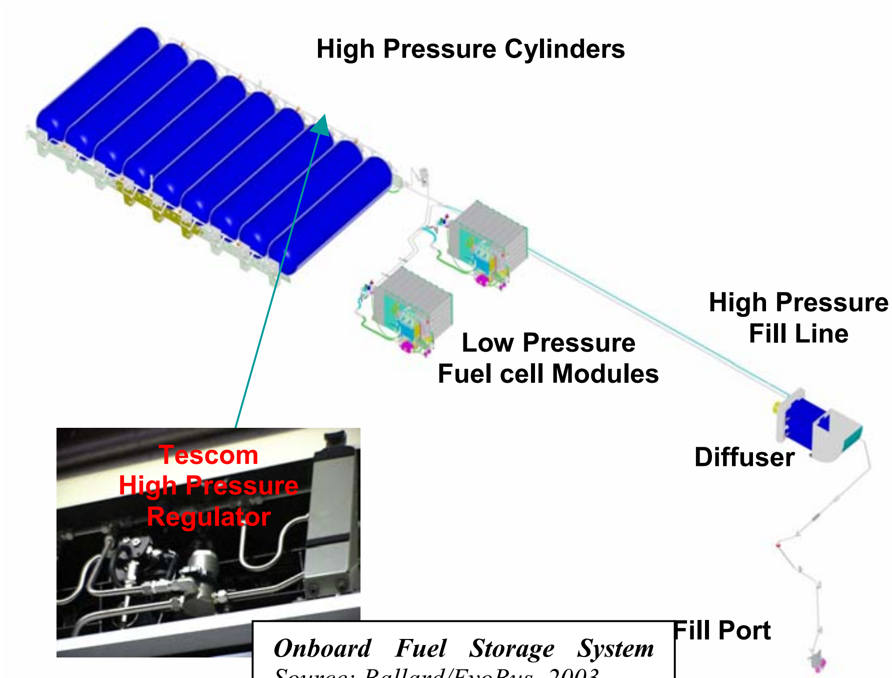




Power Characteristics Source: Ballard/EvoBus, 2003

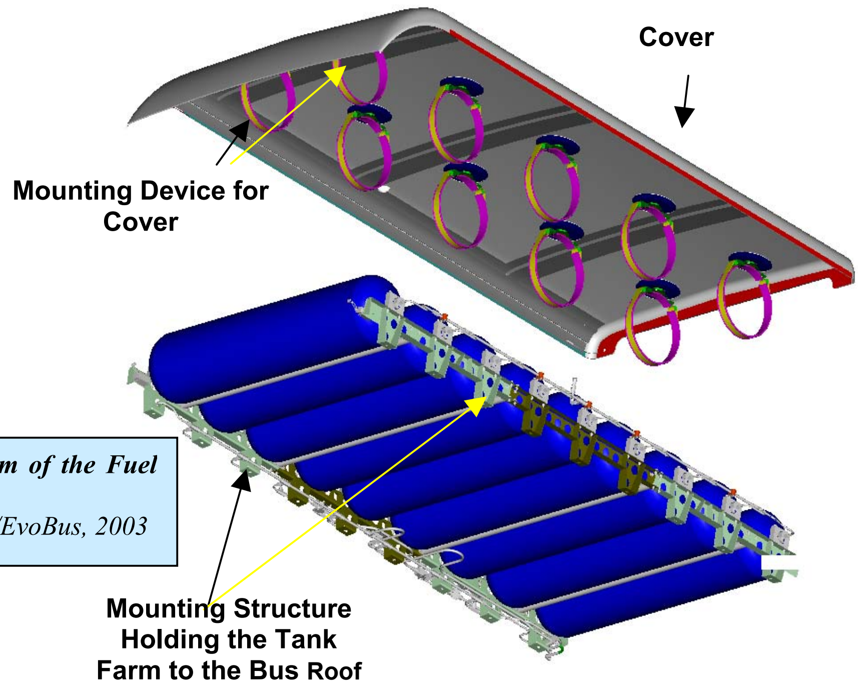
The Onboard Hydrogen Fuel Storage System

The P5-1 fuel storage system consists of 9 high-pressure cylinders of the DyneCell type with a geometric volume of 205 litres each. The total storage capacity of hydrogen at 15°C and 350 bar is 40 kg. The DyneCell cylinder is a lightweight composite cylinder designed for the storage of compressed gases such as hydrogen and natural gas. It is built from a seamless 'thin wall' aluminium liner with a full carbon fibre overwrap. The liner technology guarantees ultra-light weight, high storage capacities and non-permeability while the corrosion resistant overwrap maximises strength-to-weight ratios and operation performance under the harshest of automotive environments.



Onboard Fuel Storage System
Source: Ballard/EvoBus, 2003

The high performance design materials selected for the lightweight fuel cylinder reduces the weight of the cylinder by two- to- fourfold over conventional designs without compromising structural integrity and quality.



Mounting System of the Fuel Storage
Source: Ballard/EvoBus, 2003

With this fuel storage system, the overall weight and range requirements can be satisfied. Ranges and refill intervals may differ from those of a diesel. Range is dependent on drive cycle and cabin heating/cooling conditions. The fuel storage system is capable of fast fill operation.