05

H_2 fuel cell for transport

Architecture of a fuel cell vehicle

Index

Objectives

- The first objective is to gain an understanding of vehicle chassis developments from the time of the modern heat engine vehicle and discover the progress made with hybrid electric vehicles and fuel cell vehicles.
- To learn about the most common site of the hydrogen tank and the featured accessories leading up to the fuel cell.
- To learn about the most common site of the fuel cell.
- To learn about the most common site of the high-voltage battery.
- To learn about the site of the featured components from the fuel cell up to the electric machine and transmission.
- Obtain an overview of a fuel cell vehicle chassis. The whereabouts of the key components and the areas creating a safety risk.
- Be able to ask the right questions in the event of a breakdown and deduce the likely causes.

Introduction

When a vehicle breaks down the first thing to do is to inspect under the bonnet because this is the most likely source of the problem. The electronic box, the 12 V battery, the engine, the gearbox are all found under the bonnet. When there is no way of solving the problem it is time to call the breakdown service to tow away the vehicle or have it moved by a private vehicle.

This approach is a reflection of our knowledge about the standard vehicle chassis based on our technical know-how. However, this approach cannot be applied to hybrids or electric cars. It is important to know what happens when an electric car is towed away with the wheels of the vehicle in contact and rolling on the road. What are the most likely implications, of a situation where a high-voltage electric machine is rotated? Imagine looking for a problem under the bonnet of a fuel cell vehicle where most of the powertrain is located elsewhere on the chassis.

However, all of these changes are easy to deal with given that the technical solutions are becoming more widely known. The first prototypes of hybrid vehicles involved straightforward adjustments to the existing types of chassis, as is the case with the first fuel cell vehicles. You can still find pictures of these vehicles, where the fuel cell has merely replaced the combustion engine under the bonnet. This is no longer true for **recent vehicles, where the chassis space is maximised,** the passenger compartment and boot are retained and each key component is suitably located.

In addition to the position of the main components on the chassis, the energy circuit may be divided into 3 sections:

- The first runs from the hydrogen tank to the fuel cell
- The second runs from the fuel cell and the high-voltage battery to the electric machine
- The third section, at the front, is the standard cooling circuit

Each part of the vehicle has a specific component entailing risks of failure for the user and potential hazards for the worker.

In this unit, a new way of organising the main components on the chassis will be shown.

1.1. Teaser presenting unit 5

1.2. Comparison of hybrid vehicle powertrains

The traditional model for the modern powertrain is the front-mounted engine, transverse for front-wheel drives or longitudinal for rear-wheel drives and four-wheel drive. A further development of this is hybridisation – series or parallel – with an electric machine. Figure 1 below shows different possible architectures.

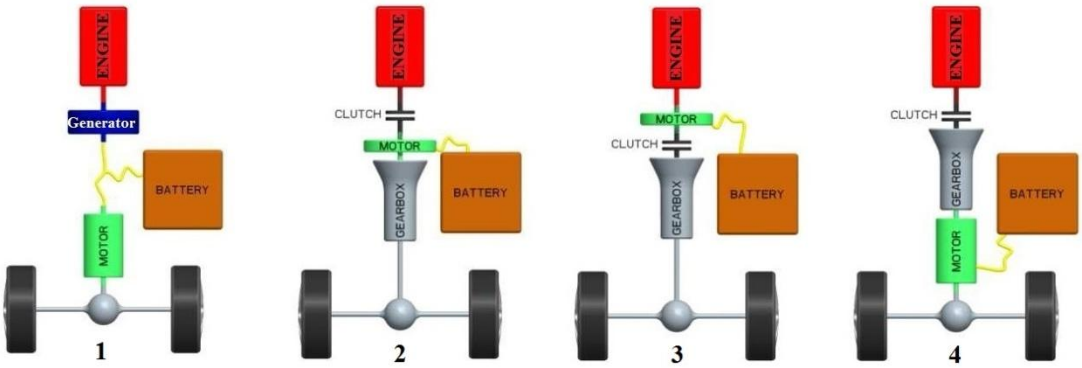

Figure 1 Diagram of series and parallel hybrid vehicles
(Source Green Propulsion).

In the series mode (1), the equivalent power generator supplies an electric motor and recharges a battery if necessary. There is no mechanical connection between the combustion engine and the wheels.

In parallel modes (2,3,4) the electric motor and combustion engine may add their power. The electric motor may be positioned before or after the clutch or alternatively after the gearbox.

The value of the series mode is the option of a **downsized** combustion engine operating when requested to its maximum torque with optimum efficiency. The value of the parallel mode is being able to use a “reduced power - increased efficiency” combustion engine in combination with the power of the electric motor. In both cases the control system will optimise the use of the engine.

The situation is nearly the same for a fuel cell vehicle. As the fuel cell is irreversible, it has to be combined with a battery or supercapacitors. The electrical connection must of course be made in parallel but two design and control modes are possible, regular or range extender. In the regular mode the fuel cell power is nearly equal to the one of the motor and the battery helps only for transient energy peaks and energy recovery. In the range extender mode the fuel cell power has been willingly downsized to the mean power of a driving cycle.

1.2.1. Range extender mode

In this mode, the fuel cell recharges the high-voltage battery which powers the electric motor. The power of the motor is chosen to achieve the required performance. **The battery then has to be able to supply the maximum current required by the motor** whereas the **fuel cell is sized to increase the operating range for an average power**. Sizing via a simulation of the running conditions is ideal to guarantee a sufficient state of charge for the battery during its operating cycle. In this case, the fuel cell power is not directly dependent on the motor but on the average power required **in an operating cycle**. Figures 2 and 3 show an example of a hybrid fuel cell go-kart designed following this philosophy.

Figure 2 FC go-kart, range extender design (source University of Liège).

Figure 3 FC go-kart, powertrain (source University of Liège).

The fuel cell is connected to a 48 V battery pack comprising 4 lead acid batteries connected in series, accepting a wide voltage range. The cell voltage is 56 V at zero current and will therefore recharge the batteries as its voltage is higher. The charging current will gradually rise and will result in the fuel cell voltage decreasing to a balancing point that will shift in line with the battery pack's state of charge. When the battery is fully-charged, the current supplied by the fuel cell will be zero but will be at maximum when the battery pack has discharged. In the event of using Ni-MH or Li-ion batteries, the same principle is applied but a DC/DC converter must be inserted between the cell and battery pack to ensure a stable charging voltage.

After the battery pack there is a 48 V chopper and permanent magnet DC motor and then the transmission to the wheels. In short, Table 1 shows the main technical characteristics of this example which will be used to compare different designs in terms of FC range extender capacity and sizing of the battery pack.

Table 1 battery characteristics of the go-kart powertrain.

Maximum motor power	5000 W
Average power required in a cycle	2500 W
Battery pack capacity	1440 Wh (48V x 30 Ah)
Battery life	35 minutes (1440 Wh / 2500 W) x 60

Here, as an example, is the additional operating range provided by the fuel cell in this running mode. Table 2 shows the calculated results based on a fuel cell efficiency of 60%.

Table 2 calculation of the additional operating range.

Type of tanks	Number of moles n (*)	Mass of H_2 in grams (**)	Joules produced by FC (***)	Additional range minutes (****)
200 bar – 2 l	16.6	33.2	2,395,787	16
200 bar – 5 l	41.6	83.2	5,989,467	40
700 bar – 2 l	58.2	116.5	8,385,.254	56
700 bar – 5 l	145.6	291.2	20,963,135	140

(*) Calculated on the basis of the ideal gas law. It is the equation of state of a hypothetical ideal gas. It is a good approximation to the behavior of many gases under many conditions. It is often written $P * V = n * R * T$ with

- ✓ P the pressure as Pa (1 bar = 1 atm = 101325 Pa)
- ✓ V the volume as m^3 (1 l = 10^{-3} m^3)
- ✓ n the number of moles of hydrogen (quantity of material)
- ✓ R gas constant = 8.31 $J.K^{-1}.mol^{-1}$
- ✓ T the calculation temperature as K (20°C = 293.15 K)

(**) A mole of hydrogen = 2 grammes

(***) The lower heating value (LHV) of hydrogen is 120 MJ/kg and taking into account the 60% efficiency of the fuel cell.

(****) On the basis of an average demand of 2.5 kW (2500 J/s)

This table clearly shows that the operating range is easily doubled with an additional 5-litre tank under 200 bar. It also shows the importance of finding a high-pressure storage mode of 700 bar as in this case the operating range is multiplied by 5 with the same tank. It is easy to make a comparison with a present-day electric car with an operating range of roughly 120 km, whereas the consumer demand is around 500 km and more.

1.2.2. Regular mode

In this mode, the maximum peak current required by the motor is provided by adding the output currents of the fuel cell and peak power system (PPS). As in the case of the range extender mode, the first thing to do is to size the motor system. The fuel cell power can be equal or just less than the motor power but in this case it will be directly dependent thereon, as with the choice of high-voltage battery. In this mode **there is no point in oversizing the battery** as this adds further weight to the vehicle. **Its role is only to raise the instantaneous power and promote the recovery of kinetic energy.**

For the aforementioned example of the go-kart, the battery capacity required to guarantee full-power operation during 10, 20 and 30 minutes for different fuel cell powers can be estimated. The go-kart is always provided with a 5 kW motor. The results are shown in Table 3:

Table 3 Influence of battery capacity in regular mode.

Fuel cell power (W)	Maximum fuel cell current (A)	Peak power system current (A)	Capacity (A.h) for 10 minutes	Capacity (A.h) for 20 minutes	Capacity (A.h) for 30 minutes
2000	41.7	62.5	500	1000	1500
3000	62.5	41.7	333.3	666.7	1000
4000	83.3	20.8	166.7	333.3	500
4500	93.8	10.4	83.3	166.7	250
5000	104.,2	0	0	0	0

This example clearly shows how the regular mode allows an additional **low-capacity battery** to be used, while reducing the fuel cell power by 10% to 20% relative to the motor power. In this example, 10% of the fuel cell power gain provides the option to keep maximum motor power for 30 minutes thanks to the PPS. The same design allows a gain of 20% on the FC power while keeping the maximum motor power during 20 minutes.

In short: the range extender mode is generally well suited to vehicles requiring a moderate power during an operating cycle although the maximum power may be high. This will be the case with vehicles frequently stopping, such as buses. The regular mode is useful for reducing the weight of the battery and as a result the vehicle for the same maximum motor power, as with road vehicles.

Table 4 below shows examples of sizing for vehicles already commercially available in small series.

Table 4 Powertrain sizing (sources Toyota, Hyundai, Mercedes).

Characteristics	Toyota Mirai Fuel cell	Hundai IX35 Fuel cell	Mercedes B Fuel cell	BUS Mercedes CITARO FC
Motor power (kW)	113	100	100	160
Fuel cell (kW)	114	100	80	120
Battery capacity (kWh)	1.6	0.95	1.4	27
Mass of H_2 in the tanks (kg)	5.8	5.6	~5	35

1.3. Scheme of a “tank to fuel cell” system

In unit 3, the safety systems available for a high-pressure tank were explained. It was also shown that a sufficient operating range involves using several tanks connected in parallel. Each one has a high-pressure solenoid valve at its output. Next are the high-pressure pipes, the cluster connection, the pressure gauge and, lastly, a second high-pressure solenoid valve. The role of this second valve is to be able to isolate the pressure regulator in the event of failure. The solenoid valves are controlled via the electronic control unit (ECU) and relays which opens them when the vehicle is operating and sometimes opens them when fuelling is required.

After the second solenoid valve one find the pressure governor, in 1 or 2 stages depending on the pressure drop. After the pressure governor one find the low-pressure pipes, in the range of 0.5 to 2 gauge bar according to the cell power.

In the case of the Toyota Mirai, illustrated in Figure 4, the filling lines do not use the solenoid valves but use a separate piping secured by check valves: 1 per line and 1 general incorporated into the external connection fitting. The pressure governor reduces the high pressure to a medium one of about 10 bars which is then reduced by injectors to the working pressure of the fuel cell. This operation is illustrated below by Yamashita et al in a publication about the Toyota Mirai tank filling system.

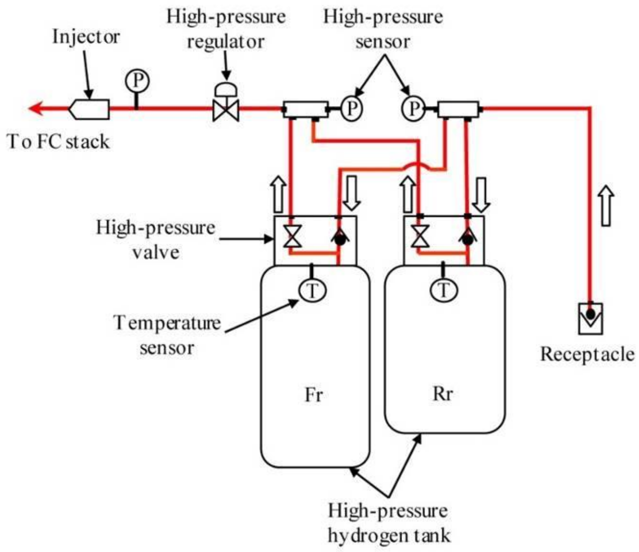

Figure 4 high-pressure tanks connection diagram [1].

Whether high or low pressure is involved, it is vital to check the tightness of the pipe connection using professional foam sprays or an electronic leak detector.

The professional standard quality foam spray creates visible bubbles when sprayed onto a leak.

Very many electronic portable models are commercially available. These highly sensitive devices measure a concentration (15 ppm – 100%) or a flow (10^{-4} mbar l/s - 10^{-2} mbar l/s). The former are easier to interpret if a hydrogen-free powertrain compartment is anticipated. **To be effective the measurement has to be taken near the source of H_2**.

1.4. Scheme of a "fuel cell to wheel" system

The fuel cell is connected to an electric vehicle but with one or two differences. The diagram in Figure 5 shows the unusual items that are found in a fuel cell vehicle compared to an electric vehicle:

- The fuel cell air supply blower
- A booster to which the fuel cell and high-voltage battery will be connected. It is common to find a different voltage in terms of the fuel cell, the battery and the high-voltage bus supplying the inverter.

The other components are common to electric vehicles:

- A low-voltage management system
- A DC/DC converter to keep the 12 V low-voltage battery charged
- A high-voltage battery (~240V) and its BMS

- An inverter supplied with high-voltage DC, reversible when the vehicle inertia drives the electric machine as an alternator
- An electric machine supplied with high-voltage AC and its transmission to the wheels

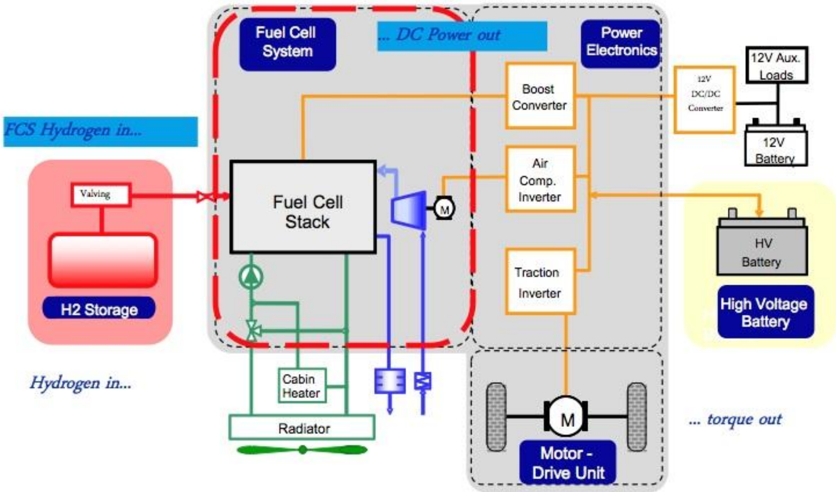

Figure 5 Diagram of the electric circuit from the cell to the motor [2].

The control of the system-derived electric energy may be explained as follows [3]:

Braking mode

The fuel cell system operates at idle and the battery absorbs the regenerative breaking energy according to the operating conditions of the braking system. Maximum current is applied and the braking simulator engages the hydraulic system in the event of a strong reaction from the conductor.

Drive mode

1) If the power required by the motor is higher than the ideal power of the fuel cell system, then the hybrid drive mode is used. In this mode, the fuel cell operates according to its rated power while the remaining power is supplied by the battery. The ideal fuel cell power may be defined as the top row of the optimum operating region.

2) If the power required by the motor is lower than the minimum fuel cell power, and the battery needs charging, the fuel cell operates according to its rated power, part of which goes to the motor system and the rest to the battery. If the battery does not need charging, the fuel cell will operate at idle and the battery alone drives the vehicle.

3) If the power required by the motor is within the fuel cell nominal operating range and the battery does not need charging, the fuel cell alone drives the vehicle. If, on the other hand, the battery does need charging, the fuel cell operates at its rated power, a part of which goes as a matter of priority to the electric motor while the other part is drawn to charge the battery.

The control process explained above continues to apply to any other cutting-edge power system such as supercapacitors or an inertia wheel instead of a high-voltage battery. This is why the term PPS (peak power source) appears in the technical literature rather than battery.

1.5. Chassis design

The chassis design consists of installing all of the components necessary for the effective operation of the powertrain. Very compact fuel cells may appear some day and they may be fitted in the same place as the combustion engine. For SUV chassis it is already possible to locate the fuel cell in the large engine compartment, it is less the case for sedan cars. Depending on vehicle type and size, many different chassis designs are possible.

That means that manufacturers will answer the question by distributing the components on the available chassis area, taking into account the energy and fluid circuits. Figure 6 shows what has to be taken into consideration:

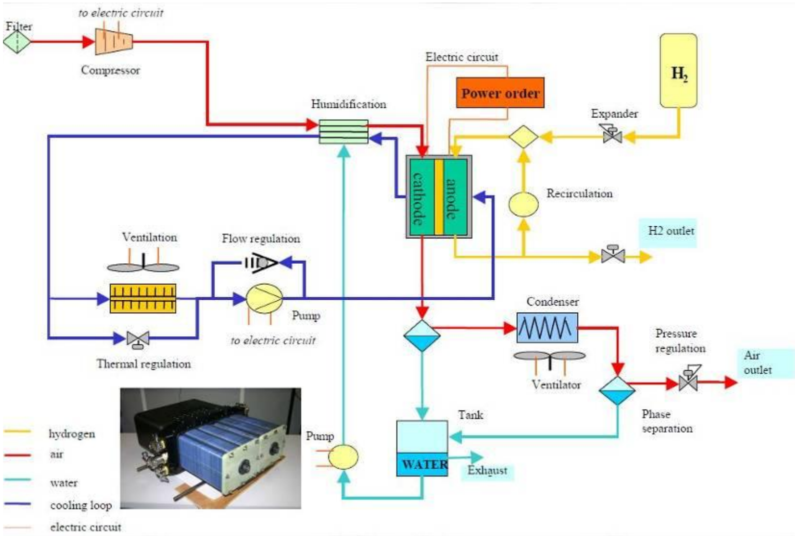

Figure 6 Fluid circuit in a FC vehicle
(source L. Antoni, Ecole Energie et Recherche, CEA Liten grenoble)

- A compressed air circuit ideally located in the front of the vehicle.
- A hydrogen circuit arriving from the tanks via the safety accessories and the pressure control. This circuit supplies the low-voltage cell.
- A hydrogen purge circuit exiting the cell and allowing it to be decontaminated in the event of reduced performance.
- A recycled water circuit arriving from the cell exhaust and supplying a humidifier placed on the air intake circuit.
- A release circuit for water produced by the cell.
- A cell cooling circuit, connected to an exchanger for heating the passenger compartment.

The first vehicle prototypes were standard ones with a traditional fuel cell being placed under the bonnet instead of the combustion engine. Honda was then the first manufacturer to offer a vehicle model marketed with the name Clarity FCX. The chassis of the first models is shown in Figure 7. The architecture was subsequently used on a widespread basis.

Figure 7 Design of a fuel cell chassis (source Honda).

The hydrogen gas tanks are located at the rear of the vehicle, where the high-voltage battery is also found. The fuel cell and its management electronics are in a central position. At the front of the vehicle are the radiators, the air supply scoop, the inverter, the electric motor and transmission to the wheels.

Figure 8 shows an example of a bus. The space available is generous at the back of the vehicle and on the roof. In view of the many tanks needed to carry 35 kg of hydrogen on board, there are a lot of connections, thus increasing the likelihood of leaks. The high position of the tanks outside any closed compartment is therefore ideal. The fuel cell system takes up space at the back of the vehicle.

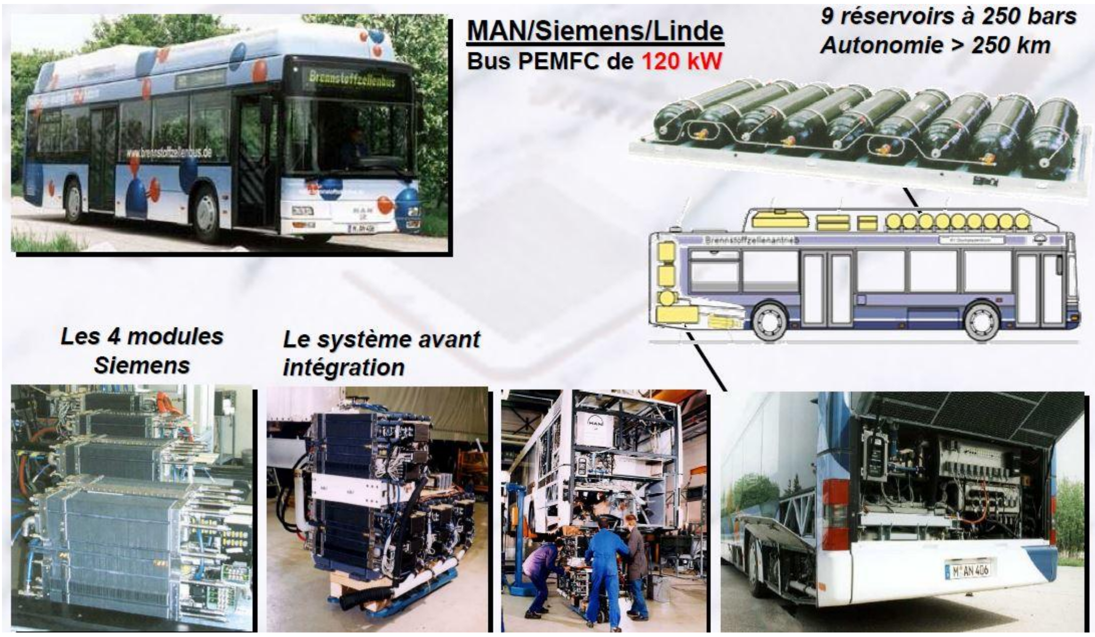

Figure 8 Establishing a fuel cell on a bus
(Source MAN/Siemens/Linde).

Figure 9 Hydrogen forklift & PowerPack (Source, Aragon Hydrogen Foundation).

Figure 9 shows the case of a hydrogen forklift. Hydrogen material handling vehicles are usually adapted by substituting the battery unit with a fuel cell powerpack. A fuel cell powerpack is a structure that includes “Fuel cell to tank” and “Fuel cell to motor” systems, providing a complete system capable of substituting the conventional batteries as the main source of energy in the same space.

1.6. Example of fuel cell powertrains

Figures 10, 11 and 12 show examples of a car chassis adapted to a fuel cell powertrain. All of the available space is used: under the bonnet in front, under the floor and under the rear boot of the vehicle. The architectures are similar in the case of the three manufacturers. These figures are followed by a video of the powertrain batch production process for the Toyota Mirai and its assembly on the vehicle chassis.

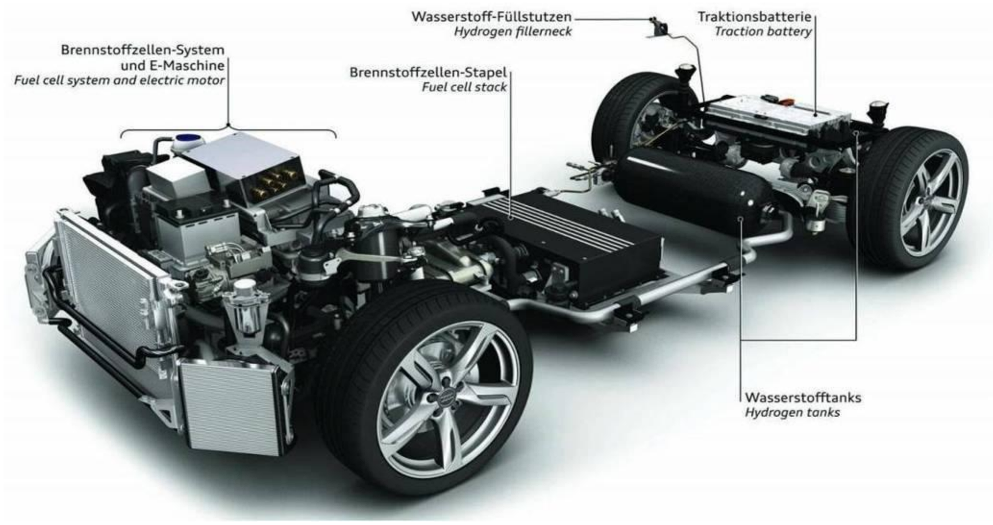

Figure 10 Example of a fuel cell powertrain (source Audi via EDUCAM).

Figure 11 Example of a fuel cell powertrain (source Mercedes via EDUCAM).

Figure 12 Example of a fuel cell powertrain (Source, Toyota [4]).

Video 1 Construction of the Toyota Mirai powertrain.

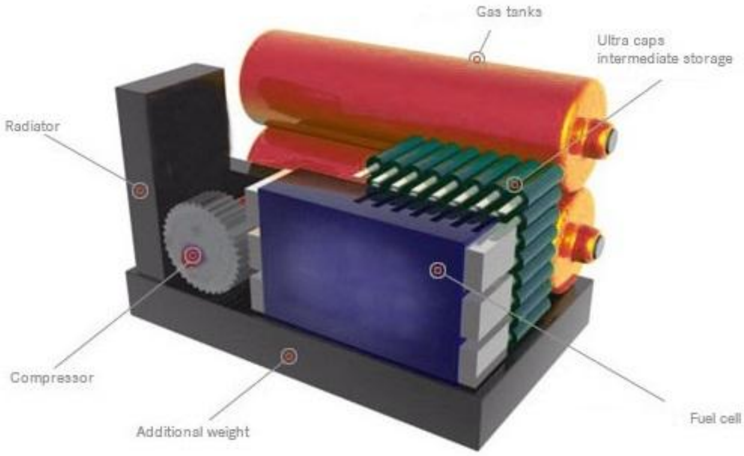

Figure 13 Example of fuel cell forklift powerpack
(Source, Aragon Hydrogen Foundation).

Figure 13 shows a hydrogen fork lift power train and some of their main blocks. Concerning material handling vehicles, a hydrogen system is always lighter than a battery pack; notice that additional weight must be included to equal the battery's weight in order to maintain the balance of the vehicle.

1.7. Safety aspects linked to the architecture

1.7.1. Risks with high voltage electricity

The main risk when working on an electric vehicle is the possibility of electric shock or the passage of current in the human body. The electrical resistance of the human body's internal tissues, from hand to hand, may be estimated at a value of between 500 Ω to 1000 Ω. Factoring in the resistances applicable to hand contact with the object provides an estimated overall resistance of 3000 Ω resulting in a current of 200mA with a 600V source. **This current is fatal after a few seconds**.

1.7.2. Chemical risks with batteries

Ni-MH batteries contain KOH, which is highly alkaline or basic. In the event of leaking, this electrolyte has to be neutralised with boric acid. Manufacturers recommend dissolving 800 g of the powder in 20 litres of water to obtain a neutralised solution. Gloves and safety goggles should be worn for this operation. During the neutralisation procedure, the PH of the escaping liquid has to be measured with a litmus paper. A PH of 7 is consistent with acid-base neutrality.

Li-ion batteries contain a dangerous electrolyte which is an irritant. This does not need to be neutralised but recovered and disposed of as chemical waste.

1.7.3. Risks of fire

Contrary to preconceived ideas, the risk of fire is not from hydrogen but from high-voltage usage. The risks occur when insulation systems are removed to carry out repairs, or subsequent to an accident. The likely causes of a fire are:

- A short-circuit between 2 poles of the high-voltage circuit
- A short-circuit between 2 phases of the electric machine and its rotation
- Failure of the BMS
- Failure of the battery ventilation system and intense heat (sunshine)

Nevertheless, if this happens, the thermal fuse of the tank will prevent an explosion by releasing all of the stored gas as a big flame.

1.7.4. Risks with High Pressure gas tanks

Handling high-pressure gases gives rise to 2 major risks:

1) In the event of a leak, the high-pressure gas spreads to occupy a large volume at atmospheric pressure, replacing the air in the room and creating the risk of the occupants being suffocated.
2) If it comes into contact with a heat source or a flame, the gas leakage could ignite or explode.

The best way to mitigate these risks is to ensure sufficient ventilation of the room. In addition, sensors of the vehicle must be active so that they will shut off the valve as rapidly as possible. Note that this last action is made possible if the sensors have all been checked at the very beginning of the maintenance work.

References

[1] Source Yamashita, A., Kondo, M., Goto, S., and Ogami, N. (2015) "Development of High-Pressure Hydrogen Storage System for the Toyota "Mirai"," SAE Technical Paper 2015-01-1169 doi: 10.4271/2015-01-1169

[2] Source: Frederick T. Wagner, Balasubramanian Lakshmanan, and Mark F. Mathias (2010) "Electrochemistry and the Future of the Automobile," *The Journal of Physical Chemistry Letters* 1 (14), 2204-2219 doi: 10.1021/jz100553m

[3] M. Ehsani, Y. Gao, S.E. Gay, A. Emadi, "Modern Electric, Hybrid Electric and Fuel cell Vehicles", Fundamentals theory and design, CRC Press, ISBN 0-8493-3154-4

[4] Mirai Technical Training manual, Toyota Motor Corporation

Summary

A vehicle chassis is highly dependent upon its powertrain. The different combustion engine vehicle architectures are already known: front-wheel drive, rear-wheel drive, front or rear engine, transverse or longitudinal engine. These architectures have undergone further development in the case of hybrid vehicles, because one or two electric machines needed to be added as an extension to the combustion engine including an automatic gearbox, power electronics, control electronics and a high-voltage battery. This chassis has undergone further changes in the case of battery-operated electric vehicles as the weight has become a key concern. Composite materials have emerged and batteries have to be placed as close as possible to the ground to ensure correct vehicle dynamics.

These alternatives to the traditional chassis nonetheless continue to be somewhat light-weight despite the changes required to install a fuel cell. In this case, all of the following components have to be established:

- A fuel cell and its control electronics
- Several high-pressure hydrogen tanks including mandatory safety components: rupture disc, fusible plug, tear-resistant nozzle/valve, manual valve and solenoid valve
- High-pressure pipes featuring the mandatory accessories: pressure gauge, solenoid valve and pressure governor
- A high-voltage battery and its control unit
- Power electronics to manage electrical energy: booster and inverter
- A synchronous or asynchronous AC electric motor

Manufacturers have thought long and hard about installing these systems on a car chassis, light commercial vehicle, bus or handling device. Some chassis are already available. Among the vehicles, the car seems to be the hardest case given the need to maintain performance, comfort, occupancy conditions and safety standards. In the light of these criteria, manufacturers have opted for different architectures that may be described as follows:

<u>Possibility 1 (SEDAN)</u>
Back of the vehicle: high-pressure tanks, high-voltage battery
Middle: Fuel cell
In front: Inverter, motor, air scoops, radiators
<u>Possibility 2 (SUV)</u>
Back of the vehicle: high-pressure tanks
Middle: High voltage battery
In front: Fuel cell, inverter, motor, air scoops, radiators
<u>Possibility 3 (large cars)</u>
Back of the vehicle: High voltage battery, inverter, motor

Middle: high-pressure tanks, cryo-compressed tank system
In front: Fuel cell, air scoops, radiators

Finally, these new chassis designs also bring new risks associated to special equipment like the high voltage battery and the high pressure tank. Fortunately these risks are mitigated thanks to the use of safety devices and the introduction of new working procedures so that safety will be on the same level as the current chassis.