02

H_2 fuel cell for transport

Basics of fuel cell for vehicles

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- **SUMMARY 14**

Objectives

- To know and identify the different types of fuel cells adapted for the transport sector: a PEFC/PEMFC for the powertrain and an SOFC as the embedded auxiliary power unit.

- To be able to briefly describe the architecture and components of a PEFC/PEMFC.

- To be able to describe briefly the working principle of a PEM Fuel Cell.

- To be aware of the important role played by water in the running of a PEM Fuel Cell.

- To be aware of the technical limitations encountered in practice.

- To be aware of general safety rules regarding the work on vehicles where some particular and risky equipment may be encountered: high-voltage battery and high pressure gas tank.

Introduction

The fuel cell is an energy converter, more specifically a means to generate electricity and heat from a fuel, most of the time hydrogen. In this context, hydrogen is considered as an energy carrier that is produced from many different primary energy sources such as fossil fuels, nuclear, solar, wind and biomass. Hydrogen can be stored in a tank, under pressure or as a liquid, instead of electricity which can be easily distributed but is difficult to store in batteries which are an expensive technology.

Unlike the internal combustion engine, a fuel cell has no moving parts and is based on a well-known principle of chemistry known as redox reactions. This topic has been covered in unit 1 of the core module, please refer to it if you don't remember exactly the meaning of redox.

A "fuel cell" car is an electric vehicle that includes specific components such as a high voltage battery, power electronics, an electric motor and transmission to the wheels.

In the case of a hybrid system, energy is stored in two separate embedded sources, first as compressed gas in a tank and secondly as electricity in a battery. Specific technical knowledge of the operation and components of a fuel cell vehicle is necessary in order to understand the possible system failures or malfunctions.

1.1. Teaser presenting unit 2

1.2. Types of fuel cells for vehicles

The fuel cell concept is quite broad. This is a battery, according to the theory of electrochemistry, for which the anode and cathode need reactive fuels to work. The operating principle is based on redox half reactions occurring at the anode and cathode. These reactions are associated by an exchange of ions through the electrolyte and electrons through the load circuit. There are different types of fuel cells as illustrated in Table 1. The lines in green are those relevant to transport applications.

Table 1: different types of fuel cells (Source, University of Birmingham).

Fuel cell types	Electrolyte	Operating temperature (°C)	Efficiency (%)	Fuel	Oxidising agent
PEFC	Proton exchange membrane	50 – 100	50 – 60	H_2 (hydrogen)	O_2 (oxygen), air
DMFC	Proton exchange membrane	Room temperature – 130	20 – 30	CH_3OH (methanol)	O_2, air
AFC	Potassium hydroxide (KOH) solution	Room temperature – 90	60 – 70	H_2	O_2
PAFC	Phosphoric acid	160 – 220	55	Natural gas, biogas, H_2	O_2, air
MCFC	Molten mixture of alkali metal carbonates	600 – 700	65	Natural gas, biogas, coal gas, H_2	O_2, air
SOFC	Oxide ion conducting ceramic	600 – 1,000	~50	Natural gas, biogas, coal gas, H_2	O_2, air

At the anode, the reaction releases electrons, while the reaction that takes place at the cathode consumes them. The electrolyte plays an important role in the exchange of ions between the electrodes. These reactions occur at a given temperature and in the presence of a catalyst.

The preferred choice for vehicle applications is the PEMFC/PEFC due to its low operating temperature and quick start up. The electrolyte is a solid membrane. The anode side of the fuel cell is supplied with hydrogen stored in a tank.

A good example of PEFC/PEMFC application is in Material Handling Vehicles (MHVs). They are specifically designed for the movement of goods, materials or products during the whole industrial and distribution cycle. Depending on the load capability and traction system it is possible to classify them in different categories: Cat. I, Cat. II, Cat. III. Figure 1 shows these three main types.

Figure 1 From Right to left: Cat-I, Cat II, Cat II MVH (Source: PLUGPOWER).

In this case, fuel cells for MHVs are usually presented as complete systems including hydrogen storage, power electronics and control. This type of fuel cell is called a powerpack and can be used in place of batteries.

Another type of fuel cell that can be found in a vehicle is an SOFC for which the high operating temperature allows for the reformation of natural gas to produce hydrogen. It is developed to work as an embedded auxiliary power unit (APU) and in parallel generates heat for the passenger compartment.

1.3. Working principles & parts

A Schematic diagram of a PEFC/PEMFC is shown in Figure 2 showing the fundamental electrochemical reactions taking place at each electrode.

Starting from the outside, we first encounter the bipolar plates that collect electrons which are conducted through the external electrical power circuit. The bipolar plates feature flow fields on one side in order to distribute the gaseous reactants over the entire gas diffusion layer (GDL).

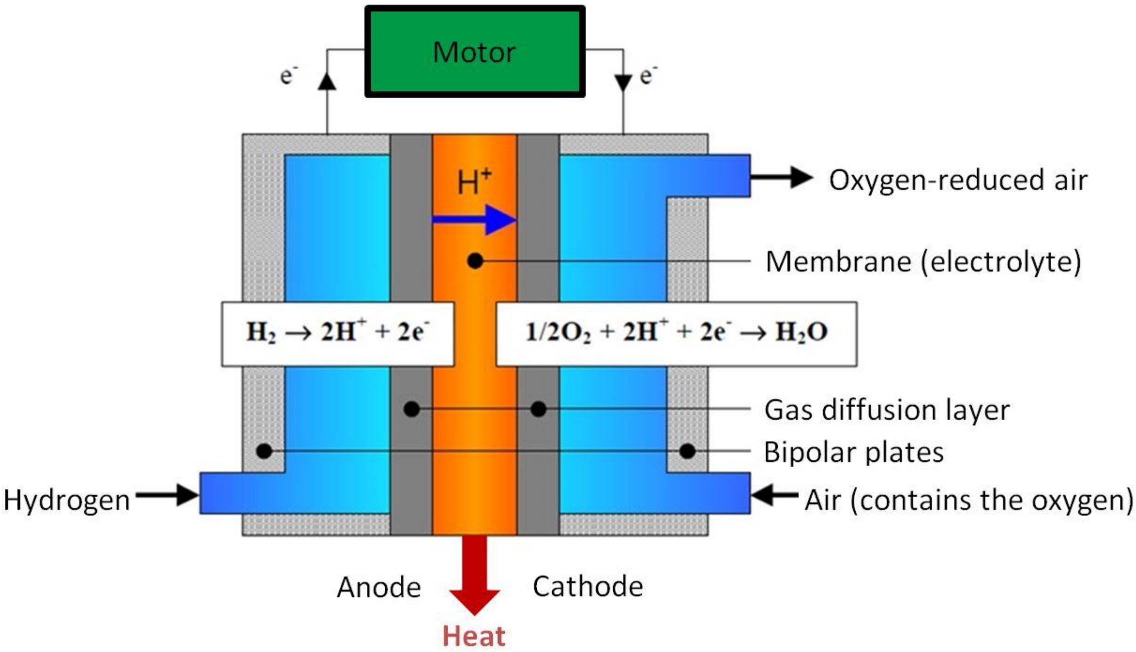
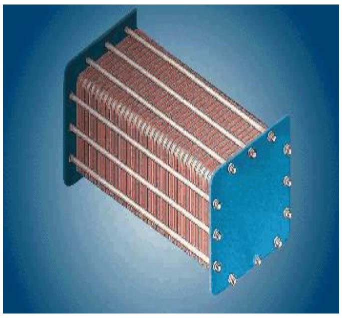


Figure 2 Schematic drawing of a PEMFC.

The gas diffusion layer is a type of graphite felt which distributes the gaseous reactants over the catalyst layer which is where the electrochemical reactions take place. The catalyst, essential for operation, is finely dispersed as a coating on the surface of the gas diffusion layer. A simplified model of a PEMFC/PEFC is shown in Animation 1.



Animation 1 Basic principle of operation of a PEMFC.

Figure 3 shows an exploded view of the membrane electrode assembly and, the bipolar plates on either end playing the dual role of mechanical supports and current collectors.

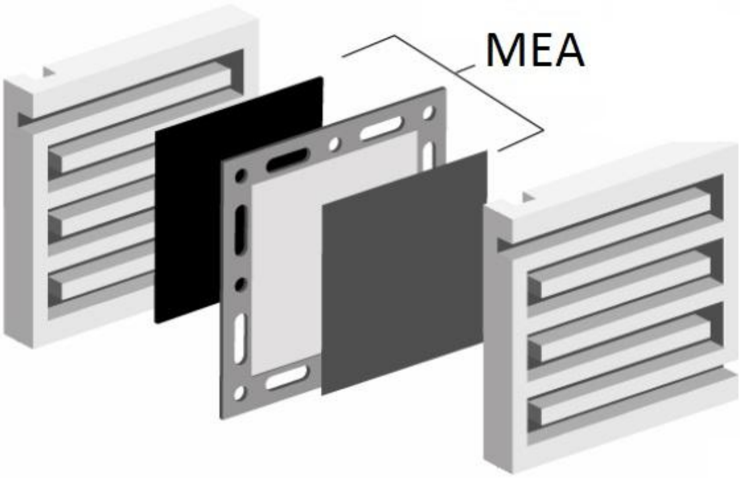


Figure 3 Schematic diagram of the components of a PEMFC (source, CEA).

Figure 4 shows an example of a membrane electrode assembly the gas diffusion layers and the electrolyte membrane. The left hand side shows the materials of an elementary cell of ± 0.8 volts. The right hand part of the figure shows a scanning electron microscope image of the MEA cross section. The red arrows indicate the fundamental electrochemical reactions that occur in the MEA.

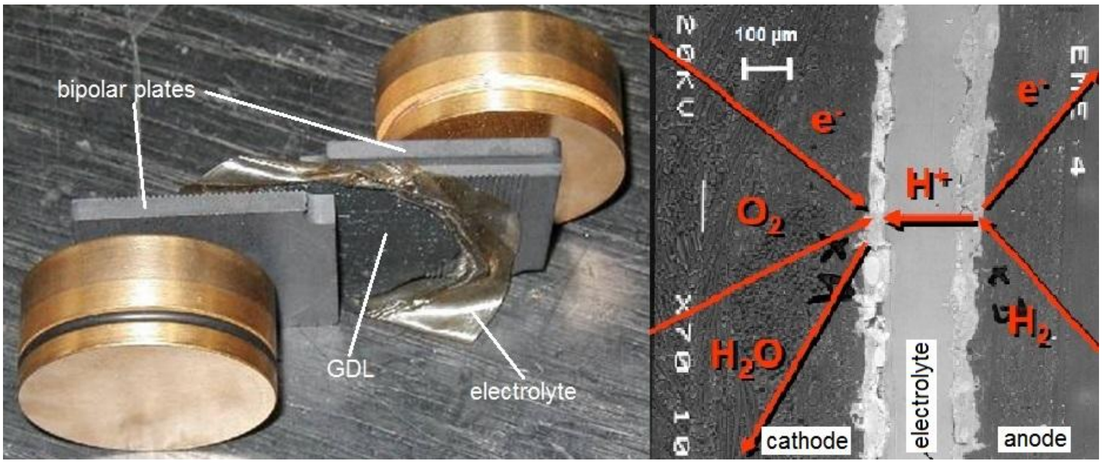


Figure 4 Example of materials encountered in a cell and for the membrane (Sources, ULg and CEA).

Similar to a battery, it is necessary to assemble the fuel cells in series to obtain a significant electrical voltage in the range of 200 - 300 V. The cells will then be simultaneously supplied with fuel. This assembly is called "the stack"; it is shown schematically in Figure 5. An example of a 500 W stack is shown in Figure 6.

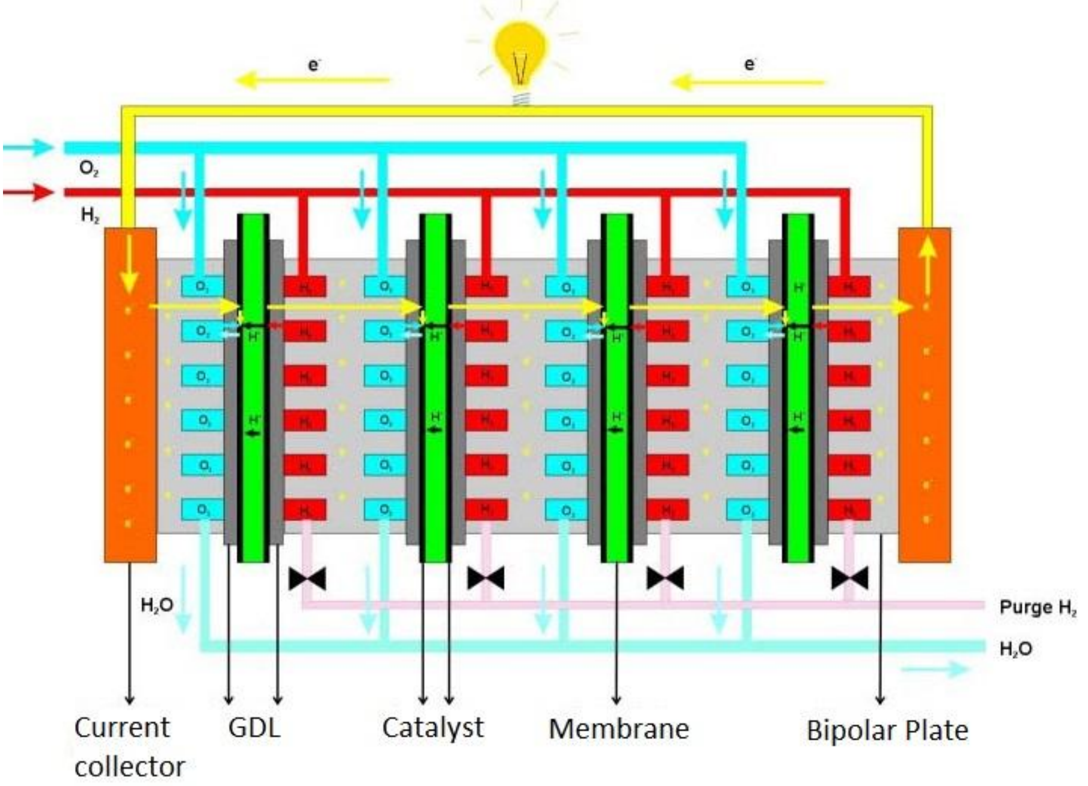


Figure 5 Assembly of cells in series.

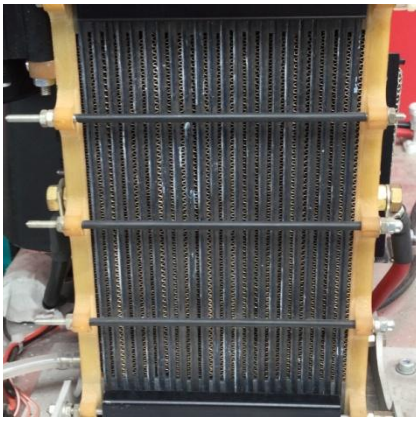


Figure 6 Stack of 22 cells in series (Source, Campus).

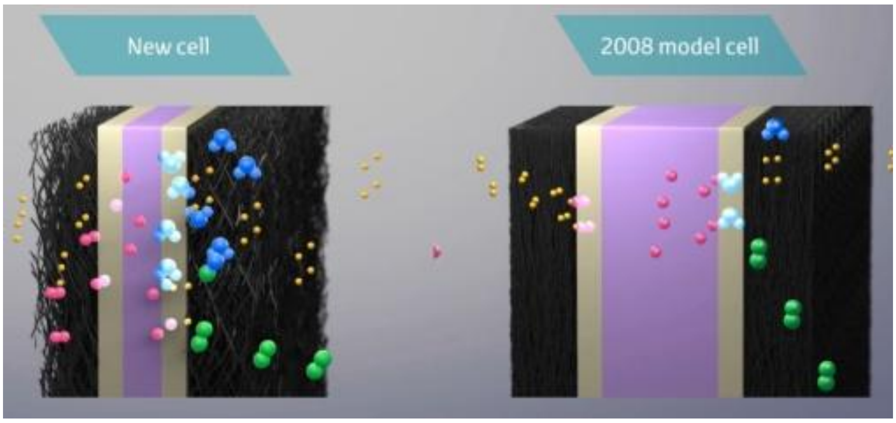
Finally, it is important to manage the operation of a fuel cell in order to monitor performance. This includes maintaining the humidity of the membrane during operation. For this reason one can sometimes find a humidifier on the air supply of the fuel cell, in the form of a pressurized spray of water vapour similar to an exchanger device. The water used is usually recycled from the exhaust. For small power units, the humidity inside the cells is controlled by the ECU which creates instant short circuits of the stack during few milliseconds.

1.4. Limitations and R&D aspects

Some technical limitations still exist that hinder the commercialisation of fuel cells. For example:

- Lack of hydrogen filling stations
- The price of some specific materials is still high
  - The platinum catalyst; to reduce this cost researchers continuously improve the nano-dispersion of platinum or are looking to use a replacement polymer.
  - The manufacture of bipolar plates and the assembly; to reduce this cost drastically, the stamped plates are preferred to the machined plates as long as the dimensional tolerances remain low.
  - A 1 kW PEFC/PEMFC costs about €2,000 in niche product. It is projected in 2020 to reach a reduced cost of €50 per kW for an average power of 80 kW delivered by a PEMFC produced at a rate of 500,000 units per year.
- It is necessary to increase the performance which can be achieved by operating at higher hydrogen pressures.
- Satisfactory service life must be guaranteed.
- Users should be made aware that technology nowadays abides by strict safety standards. A complete description of the technology requirements must be disseminated to avoid any risks under normal conditions and also in the event of an accident. If a vehicle is on the road, people must know that it meets the safety standards and therefore that it is safe and reliable.

To demonstrate progress of the R&D process, car manufacturers that rely on hydrogen often present the most significant results in the form of instructional videos like that shown in Animation 2 by Toyota. This video highlights the progress made by their fuel cell in terms of power density, water management, durability and reliability.



Animation 2 Demonstration of R&D progress (Source, Toyota).

1.5. General working procedures with high voltage components & high pressure tanks

1.5.1. Professional sector certifications

These topics are very important as they involve the health of workers. They are subject to specific rules defined by standards. In addition, there are Professional Sector Organisations that bring together all stakeholders for business, technical & social discussions including the development of training programs. These organisations may concern the industry sector, garage & maintenance sector, the transport sector etc.

One of the missions of these organisations is to deliver training and certification to workers. In the example of Belgium, they are addressed to different audiences and are organised in 3 levels:

Level 1: informed workers do not work on dangerous parts of the vehicle but they must be aware of the intricacies of the vehicle.
Level 2: skilled workers work on sensitive systems after isolation (technicians, body repairers, repairers).
Level 2 (diagnostic): skilled workers perform the fault diagnosis, he works on sensitive systems connected to high voltage HV (diagnostic technician).
Level 3: technicians who obtain this label are finally able and authorised to assume trainings about technology and safety aspects.

1.5.2. Identification of vehicles

Given their characteristics and associated safety procedures, it is absolutely necessary that workers and first responders should be able to quickly recognise a special vehicle. That is why manufacturers have provided appropriate signage.

For the moment, this signage is quite flashy as seen in the example of Figure 7, because the fuel cell vehicle is also a demonstration of a new piece of technology by a manufacturer. This logo will quickly start to resemble the one shown in Figure 8 as the public will become more and more familiar with this new technology.

Figure 7 Identification of an industrial FC vehicle (Source, STILL).

Figure 8 Identifying logo of a vehicle (source, Toyota).

1.5.3. Personal protection equipment & specific tools

The most exposed parts of the body are the hands and eyes which must be protected using insulated gloves and glasses or helmet with a visor. As for the battery electric vehicle, insulated tools and a voltage detector are used instead of a multimeter in the isolation phase. Furthermore, the worker will isolate himself from the ground by wearing insulated boots or shoes. In some instances, the worker will also wear special trousers and a jacket.

Figure 9 Example of protective equipment and specific tools
for working on HV systems.

One can see some examples of specific tools in the Figure 9. You will recognise:

1. Voltage detector which performs voltage measurements without the need to adjust any settings. It must be tested before use, for example, with a 12 V battery.
2. Helmet with a visor for eye protection.
3. Isolated pliers, wrenches and a ratchet for mechanical purposes.
4. Gloves. The choice of insulated gloves must meet certain requirements and standards. European legislation requires to clearly indicate the level of insulation against electrical transmission which detailed in the EN60903 standard. The gloves must be tested before use by inflating in order to detect any small holes.
5. Signalling banners.
6. Service plug. It must be removed for the isolation of a high voltage battery/FC and kept by the worker.

It is also recommended to perform electrical measurements using only one hand as using both hands would provide a path for the current to pass through the heart in the event of an electric shock. As a result, alligator clips are used in place of measuring probes.

1.5.4. Signage when working on a vehicle

Figure 10 Examples of hazard signs
found on potentially dangerous systems.

1.5.5. Manual neutralisation of high voltage (HV) & high pressure (HP)

When the ignition key is removed from a vehicle, the high voltage is switched off because the battery is normally equipped with open relays. This security measure is, however, not sufficient as it is also necessary to remove:

- the service plug placed in the high voltage circuit of the HV battery
- the service plug placed in the high voltage circuit of the Fuel cell

Always wear insulated gloves to perform this operation. If the service plug is removable, the technician responsible for its removal must keep it in their possession to prevent another person from replacing it by mistake.

The absence of voltage must be observed by means of a voltage detector and not a multimeter as an improper adjustment of the latter will give false readings to the user. Ideally, the voltage detector must be tested before and after use with a 12 V battery, for example.

Similarly, concerning the high pressure system, upon removal of the ignition key, a solenoid valve closes the pressurised gas tank. Similar to the high voltage system, some additional precautions are necessary:

1. Check the detection sensors in the garage. As soon as work on hydrogen components is carried out, it is expected that hydrogen gas will be present in the air. That means that we must accept a certain concentration and obviously reject it over a pre-defined threshold value. Therefore, the sensors or detectors will be selected in relation with an expected level of concentration associated to a specific activity. Table 2 shows this relation between the type of activity and the expected concentration limits. This table also associated the types of safety topics & safety devices concerned for each subdivision. Concerning the choice of the warning thresholds, there is still no available standard so the present information is valuable.

2. Check the ventilation system; this is very important as garage sensors will automatically increase the ventilation if the measurement reaches a defined threshold.

3. Follow the instructions of the manufacturer to shutoff the tank. Information concerning the manual shutoff valve of the tank should be present.

4. Slightly unscrew the connector of the line and carefully listen to any audible noise of a gas leak.

5. Wear the personal safety device and be sure that the personal hydrogen detector is switched “ON” upon entering the room.

Table 2 Estimation of hydrogen gas concentrations in the working environment

H_2 concentration high in ppm	H_2 concentration low in ppm	Safety topic	Safety device
1000	1	Maintenance work	Personal safety device
10000	100	Personal safety	Alarms, system failure
10000	100	Avoid imminent danger	Automatic ventilation increase
10000	1000	Built-in safety measures (also check off)	Automatic shutdown
100000	10000	Combustion, explosion	Danger, effects on human body

1.5.6. Safe disconnection / reconnection of hydrogen tanks

After following the safety precautions listed in Section 1.5.5, the topics on how to safely disconnect a hydrogen tank and reconnect it after maintenance can be covered.

Concerning the safe disconnection after manual closing, the precaution is to slightly unscrew the tank connector and carefully listen for any sign of leakages.

For reconnection it is more complex as we have to pay attention to 5 technical requirements:

1. Check sealing surfaces for dust or damage
2. Always replace the pipe removed as its connector has been deeply deformed
3. If the counterpart seal is a copper ring, it must also be changed
4. Use the right torque specified by the supplier to tighten the connector
5. Check the tightness using the method described by the vehicle manufacturer and make this at the appropriate pressure also indicated in the procedure. This pressure will probably be high, close to the maximum, as a leakage is then easier to detect.

1.5.7. Check list before resetting nominal conditions

Before placing into service, it is advisable to inspect the vehicle and check whether the tasks have been performed correctly by following the standards and the manufacturer's instructions. It is also advisable to once again inspect all of the hotspots, high-voltage parts, high pressure components and piping.

The role of this check list is to simplify the final visual inspection as the person responsible for operation will have the file of the parts concerned for maintenance. They will look for unexpected bad connections or damages.

Summary

A fuel cell operates on the principle of redox reactions and there are no moving parts. Its operation depends primarily on the material used for the electrolyte and reactant gases.

There are actually several types of fuel cells, generally known by the name of their electrolyte. The fuel cell type typically used in the automotive powertrain is the proton exchange membrane fuel cell or PEMFC. It is also possible to find solid oxide fuel cells or SOFCs as embedded auxiliary power units or APUs.

An elementary cell of PEMFC/PEFC consists of bipolar plates, the gas diffusion layers coated with a dispersed catalyst and an electrolyte membrane. A fuel cell stack is made up of a series arrangement of elementary cells. The stack assembly is capable of producing several hundred volts.

In addition to the reactant gases, water plays an important role in the ionic transport phenomena through the electrolyte membrane. The humidity content must be kept optimum during operation. In this condition, the average efficiency of a fuel cell is about 60%.

Upstream of the fuel cell we have a high pressure gas tank and a supply line. Downstream of the stack, we are in the context of an electric vehicle and therefore we can find a high voltage battery, power electronics, an electric motor and the transmission. Both technologies have risks that are taken into account by professional sector organisations which organise trainings where safety is always a key point. The student will learn:

- To recognise the special vehicles thanks to their identification & logo
- To use the individual protection equipment
- To indicate the dangers by using specific signage when working on a special vehicle
- To know all of the actions to safely isolate the dangerous parts of the vehicle, battery and tanks
- To check the isolation of dangerous parts
- To know all of the actions which are necessary to disconnect and reconnect the high pressure tank
- To perform a “check list” before reconnection of the HV battery and opening of the manual high pressure valve of the tank.

It has been shown that each time about 5 action points are necessary to perform basic maintenance operation, 4 of which concern personal safety issues. The main role of this training is to insist on the fact that these safety operations are not an option.