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OVERVIEW OF SAFETY IN HYDROGEN PRODUCTIOON

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بسم الله الرحمن الرحيم
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Dedication:

This humble work is dedicated to: My dear parents who have always been there to encourage and motivate me. All My friends and classmates

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Firstly, I want to thank ALLAH who gives me courage, health and strength to accomplish this work. I would like to express my deepest appreciation to my lovely family for their greatest support. Special thanks to my supervisor Mrs. **Aissani nassima** for her guidance, advice, encouragement, and valuable help in achieving this research. I would like to extend my thanks to the members of the jury for the time and the efforts spent in reading this work. My best gratitude to all teachers of the department for their patient guidance, for their continuous attention and help they have been giving during the five years. Alongside, I would like to express my sincere thanks to all those who contributed to this work.

Sommaire

List of acronyms and abbreviations

RES	renewable energy Sources
SR	the steam reforming
APR	aqueous phase reforming
SMR	steam methane reforming
LTS	.low temperature shift
HTS	high temperature shift
WGS	The water-gas shift
SR	Steam reforming
EIS	Electrochemical Impedance Spector’s
TARGET	Team to Advanced Research for Gas Energy Transformation)
EIHP	the European Integrated Hydrogen Project
LHV	Lower Heating Value
SMR	Steam methane reforming
CI	compression ignition
FCEV	Fuel Cell Electric Vehicle
EV	electric vehicle
PEM	polymer electrolyte membrane
LVS	low-voltage side
HVS	the high-voltage side
FTA	Fault tree Analysis
PEMFC	proton-exchange membrane fuels cell

List figure :

List table:

1 Introduction:

Hydrogen and energy have a long shared history. The first demonstrations of water electrolysis and fuel cells captured the imagination of engineers in the 1800s. Hydrogen was used to fuel the first internal combustion engines over 200 years ago. Hydrogen provided lift to balloons and airships in the 18th and 19th centuries, and propelled humanity to the moon in the 1960s. Hydrogen in ammonia fertiliser (from fossil fuels and, earlier, from electricity and water) has helped feed a growing global population. And hydrogen has been an integral part of the energy industry since the mid-20th century, when its use became commonplace in oil refining.

The production of hydrogen needs both a hydrogen containing compound and energy to extract it. In general, the processes used for its production can be divided in three: thermal, biological and electrochemical. In thermal processes, the most commercially developed, a hydrogen containing compound such as natural gas is catalytically transformed in the presence of water steam which provides thermal energy, a process known as methane steam reforming. The result of such reaction is a hydrogen rich mixture of gases which later go through an enriching (water shift reaction) and a purification stage (typically pressure swing adsorption). New processes less thermally demanded are being developed to lower hydrogen price. This type of process can also be used with different hydrogen containing compounds but the longer their molecules the more difficult is the extraction of hydrogen. In general MSR and other similar paths depend strongly on feedstock prices, i.e. natural gas prices, and are not 100% clean methods due to CO2 generated during hydrogen production. Some approaches to this, consider carbon sequestration in conjunction with clean electricity generation to gain from hydrogen benefits. Other thermal processes include chemical cycles where a “commodity” product (intermediate chemical compound) is generated to store primary energy in order to later use it for hydrogen production. Such processes are being explored but have not reached yet competitive costs compared to commercial hydrogen. we will position Hydrogen among clean energy and will study safety in hydrogen based process.

Memory structure

Chapter 1

This chapter describes global trends in renewable energy and discusses market growth, barriers, high-impact opportunities, as well as future scenarios and the scale of the challenge for hydrogen as source of energy.

Chapter 2

In this chapter, we study the beginning of hydrogen production and use, how it was produced, and how it was stored

Chapter 3

The basic understanding of vehicle performance, power plant characteristics, transmission characteristics, and the equations used to describe the vehicle performance are introduced. The main purpose of this chapter is to provide the basic knowledge that is necessary for vehicle drive train design to be analyzed in next chapter.

Chapter 4

Understand the hazards and safety provisions associated with hydrogen and fuel cell engine systems. Hydrogen fuel cells have the potential to dramatically reduce emissions from the energy sector, particularly when integrated into an automotive application. However, this is hurdle to the commercialization of this promising technology, which has proven difficult to achieve to date. This hurdle can be overcome through in-depth reliability analysis including techniques such as Failure Mode Fault Tree Analysis (FTA).

This thesis end with conclusion and some recommendations using hydrogen

chapter1 : Clean energy in the world

1 Introduction

The Paris Agreement, a new climate treaty adopted by 196 signatory parties of United Nations Framework Convention on Climate Change at COP-21 set the milestone for reducing global warming to keep the average global annual temperature increase below two degree Celsius which is to be achieved by the year 2100 through limiting the greenhouse house emissions using leading science and technology [1]. The world has seen the increase in the use of RES, while reducing the dependence on the conventional fuels, as one of the solutions to achieve this objective. Figure 1.1 show the renewable energy generation around the world since 1965 using hydro power, solar power, wind power and other sources like geothermal and biomass based on the data published by in the 70th edition of the statistical review of world energy [2]. Hydro power has always been a leading renewable energy source and it can be seen that the use of wind and solar energy has seen considerable rise in last decade. A lot of research has been carried out in order to make the harness of these RES more efficient, eco-friendly and cost effective so that they can compete with the conventional energy sources such as petroleum and coal to shift the balance towards green energy.

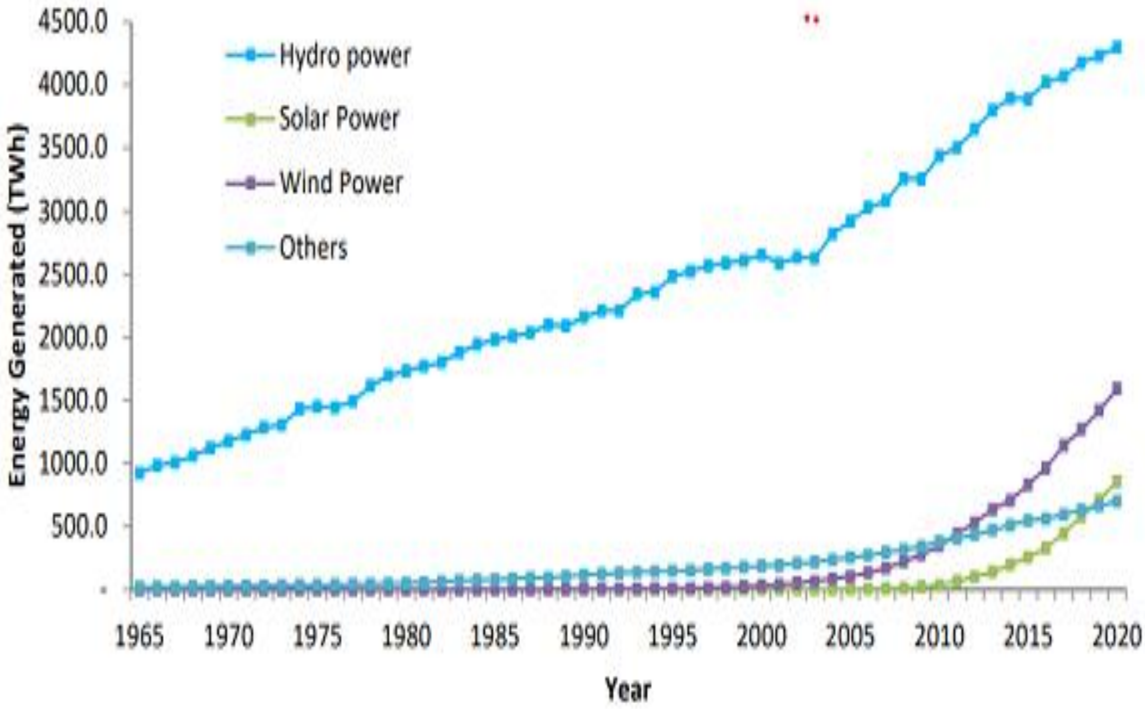


Figure 1-1 : renewable energy generation around the world.

Table 1-1 :renewable energy target to be achieved France In this project we focus on hydrogen production process and how much is it safe.

Renewable Energy Source	Targets to be achieved	
	by 2023	by 2028
Solar Energy	24.1 GW	33.2-44 GW
Wind Energy (Onshore)	24.1 GW	33.2-34.7 GW
Wind Energy (Offshore)	3.4 GW	5.2-6.2 GW
Hydroelectricity	25.7 GW	26.4-26.7 GW
Biomass	145 TWh	157-169 TWh
Geothermal Energy	2.9 TWh	4-5.2 TWh

2 Clean Energy in the world

Clean energy is energy gained from sources that do release air pollutants, while green energy is energy derived from natural sources. There is a subtle difference between these two energy types even though they are often spoken of as being the same.

Renewable energy is power generated from sources that are constantly being replenished. These renewable energy resources won’t run out, unlike fossil fuels and gas, and include wind and solar energy.

However, while most green energy sources are renewable, not all renewable energy sources are seen as being green. For example, hydropower is a renewable resource, but some would argue that it is not green, since the deforestation and industrialization related to the building of hydro dams can damage the environment.

The perfect clean energy mix occurs where green energy meets renewable energy, such as with solar energy and wind energy.

An easy way to remember the differences between these different energy types is:

- Clean energy = clean air
- Green energy = natural sources
- Renewable energy = recyclable sources

Clean energy works by producing power without having negative environmental impacts, such as the release of greenhouse gases like carbon dioxide. A lot of clean energy is also renewable, including wind power, some hydro resources and solar powered energy generation.

The most important aspect of clean energy are the environmental benefits as part of a global energy future. While clean, renewable resources also preserve the world’s natural resources, they also reduce the risk of environmental disasters, such as fuel spills or the problems associated with natural gas leaks. With fuel diversification, through different power plants using different energy sources, it is possible to create reliable power supplies to enhance energy security, ensuring there is enough to meet our demands.

Clean energy provides a variety of environmental and economic benefits, including a reduction in air pollution. A diverse clean energy supply also reduces the dependence on imported fuels (and the associated financial and environmental costs this incurs).

Renewable clean energy also has inherent cost savings, as there is no need to extract and transport fuels, such as with oil or coal, as the resources replenish themselves naturally.

Other industrial benefits of a clean energy mix are the creation of jobs to develop, manufacture and install the clean energy resources of the future.

Clean energy can be used for a variety of different applications, from electricity generation to heating water and more, depending on the source of the energy.

Solar energy can be used for heating and lighting buildings, generating electricity, heating water directly, cooling and more. Solar panels allow for energy from the sun to be collected and turned into electricity. Solar panels are frequently used for small electric tasks, such as charging batteries, while many people already use solar energy for small garden lanterns. However, this same clean energy technology can be scaled up to larger panels that are used to provide power for homes or other buildings or even installations of multiple solar panels, such as with a community solar panel array to power entire towns.

Water is another clean resource with some surprising applications. Most obvious are hydroelectric power plants, which take the flow of water from rivers, streams or lakes to create electricity. A less obvious use of water comes through municipal pipes in towns and cities. With lots of water running through pipes in homes each day, there is a move towards harnessing this energy to help meet domestic and other power needs. As generators become smaller and less expensive to build this use of municipal water is becoming closer to being a daily reality.

Wind power works by attaching a windmill to a generator which turns the turning of the windmill blades into power. This form of energy has been used for centuries to grind grain, pump water or perform other mechanical tasks, but is now being used more often to produce electricity. Onshore and offshore wind farms are becoming increasingly prevalent, but wind power can also be used on a much smaller scale to produce electricity, even to provide a source of power for recharging mobile telephones.

These examples of renewable sources can be added to by others, such as geothermal, biomass and Green Hydrogen, which also all have their own benefits and applications.

All clean energy sources are, by definition ‘clean,’ however not all renewable energy sources are clean. For example, burning wood from sustainably managed forests can be renewable, but it is not clean since this releases carbon dioxide into the atmosphere.

To be truly clean the carbon cost of production and storage needs to be zero, and this is where sources such as solar power and wind energy are seen as being truly clean and renewable. In Hydrogen production we must distinguish clean Hydrogen and conventional hydrogen.

3 Well known and used clean energies:

3.1Solar énergie

The incident solar power on the planet is 166 PW; 30% of this is reflected back into space, and 19% is absorbed by clouds. This leaves a balance of 85 PW available for terrestrial solar collectors. This figure of 85 PW not only shows that solar power is well over 5000 times our current world 15 TW power consumption, but all other sources are less than 1% of solar. If we consider only the solar power that hits the desert regions of the world, all other renewable still only amount to less than 3% of this power. This clearly demonstrates that solar is where humankind’s effort must stay focused for the future. Although alternative renewable only supplies less than 1% of solar, they still can be justified for niche power in cold countries and also providing some backup security for critical utilities in case of natural disasters.

This is why solar power ultimately makes economic sense. There is so much available power that any conversion inefficiencies can be more than compensated for by investing in the nonrecurring cost of more solar collectors. There is clearly so much solar power available that extra energy can be generated during the day for night use, by storing the power. The current trend in consumption patterns show a decrease in night consumption and an increase in the day hence, losses due to storage will steadily decline and can also be compensated by more collectors. In the forgoing subsections, we identify the dominant collection technology. However, given that there are many methods of collecting solar power, in the following, we focus on two main contenders: solar cells and solar thermal collectors. [2]

3.2 **Solar Cells**

Silicon photovoltaic (PV) solar cells are a convenient means of powering silicon microcircuits, such as pocket calculators. However, if we now pose the question of powering 15 TW with solar cells, we can identify their weaknesses in terms of efficiency and environmental impact as compared to the low-tech solution of solar reflector dishes driving steam turbines. To calculate the solar panel area required to supply 15 TW, consider an average solar irradiance (insulation) of 300 W/m2 and an optimistic average efficiency of 20% over the solar cell lifetime. This results in a total panel area of 100 km by 100 km in order to power total world consumption. For silicon semiconductor processing, it has been estimated that for each square centimeter of chip area it takes 20 kg of water and 4.5 g of chemicals during manufacture [3]. However, given that a solar cell is much simpler than a silicon microchip, requiring far fewer processing steps, let us optimistically reduce these figures to 10% giving 2 kg/cm2 of water and 0.45 g/cm2 of chemicals consumed during manufacture. This results in a total water consumption of 2×10^{17} g. This is equivalent to 3×10^{8} g of water consumed every second over the 20-year lifetime of the solar cells. This is not far off the same order of magnitude as the amount of water required for electrolysis per second in a world-scale hydrogen economy. However, in the case of solar cells, the figure of 0.45 g/cm2 implies that the total water use is contaminated by 4.5×10^{14} g of chemicals at a concentration of 400 ppm. By contrast, a solar hydrogen economy burns hydrogen that produces water, which re-enters the environment in a clean way. Each solar cell, for example, uses about 0.17 g/cm2 of arsenic11 during manufacture, and thus for a panel area of 100 km by 100 km we need 6 million tones of arsenic. Unfortunately, the world reserve base of arsenic lies at as little as 3 million tones [4]. Moreover, CdTe solar cells consume 6.5 g/m2 of tellurium (Te), CIGS cells use 2.9 g/m2 of indium (In), aSiGe cells use 0.44 g/m2 of germanium (Ge), and dye sensitized cells use up 0.1 g/m2 of rubidium (Ru) [5] Vin all cases world reserves would be stretched, particularly if we take into account the finite lifetime of solar cells. This motivates the need for a more detailed viability analysis for all the chemicals used in solar cells. For an inventory of the toxic chemicals used in solar cell manufacture, and their hazards, see [6]. In terms of powering the world, a simple argument based on thermodynamics shows that PV solar cells are fundamentally unsuited for our aims. Consider the fact that the Sun's rays can be easily concentrated or focused down, resulting in temperatures as high as 1000 C. Simple thermodynamics tells us that it pays to exploit large temperature differences in order to approach ideal Carnot efficiency. This immediately tells us that a low-tech solution that involves boiling water and running a steam turbine, will fundamentally always be superior PV solar cells simply do not exploit temperature. This tells us that solar cells are ideally suited to energy harvesting at lower powers and temperatures thus are not ideal for heavy base-load energy demand. The efficiency of PV solar cells can be increased by concentrating the light to create higher incident intensity. But focusing the Sun's rays also increases temperature. Because PV solar cells are a semiconductor technology there is a limit to the temperatures they can withstand. As temperature increases, semiconductor reliability dramatically drops and reversed biased leakage currents exponentially increase. Hence, cooled concentrated light PV cells achieve some gain, but fundamentally can never fully exploit the focusing power that solar-thermal collectors can withstand. Concentrating the light can reduce the solar cell area required but given that solar cells need replacement and that light concentration will cause a drop in cell lifetime, the consumption of chemical resources is still untenable. A factor that demands further analysis is light-induced degradation of solar cells [7], where performance drops with continued exposure of PV cells to light due to formation of semiconductor defects. This effect will be greatly accelerated in cases where light is highly concentrated providing around the equivalent of 500 suns incident on a PV cell. Thus claims that such concentrated solar cells can achieve 9 40% efficiency must be tempered with realistic lifetime issues and consequent consumption of resources.

3.3**Solar Thermal Collectors**

The previous subsection, argued against solar cells as they are not ideally suited for exploiting focused sun. Therefore, in this subsection we cut to the chase by going straight to the method that optimally exploits this fact. This method is called solar thermal. The idea is to use a curved mirror to focus sunlight on a container of water to create steam. Due to the high temperatures, the steam is superheated and can efficiently run a turbine connected to a generator to produce electricity [8];[9]. At present there are 340 million m2 of solar hot water collectors in the world. In Appendix B we perform calculations that demonstrate that the planet has plenty of unused deserts to supply the world’s energy needs many times over, using solar thermal. Fig. 1.2 shows a solar thermal system that has already demonstrated 20-year functioning performance in California’s Mojave Desert, which currently outputs 354 MW of power [10]. This system illustrates long-term reliability with no signs of malfunction, over the last 20 years. The principle of operation is that a trough style reflector focusses sunlight down to a line and heats a pipe containing oil. The oil goes through a heat exchanger and is cycled back, and the heat is used to create steam. The resulting steam is used to drive Rankin cycle turbines, for producing electricity. The idea of the trough-shaped collector is that it makes tracking the sun simpler and eliminates shading along one axis.

Figure 1-2 :The Solar Energy Generating Systems (SEGS) solar trough farm at Kramer Junction, California.

4 Wind Power

Wind power is an increasingly popular renewable source and produced as much as 100 GW world-wide in 2008Vit is also a path to producing a renewable source of hydrogen for energy storage or as an energy carrier [11], [12]. Wind power can potentially generate a maximum of 72 TW in theory [13]. However, in practice, wind power is likely to only expand to a fraction of 72 TW and thus is not a dominant candidate for supplying the whole world's energy For example, a Californian study found that bird fatalities per MW per year, due to impact with wind turbine blades, are in the range of 0.8 to 2.0 birds per year [14]. If we optimistically take the low end and assume one fatal bird impact with turbine blades per MW per year, then if we supply the world's 15 TW of energy with wind power alone then this corresponds to 15 million deaths per year. Given that over 1000 bird species are approaching extinction, this means that the location of wind farms will be a sensitive issue. This can be managed by simply locating wind farms strategically away from avian migration pathways in fact, in the United States it is illegal to kill a migrating bird, and thus such policies will drive location. Couple this with other restrictions on location such as keeping distance from high population densities, distance from sites of aesthetic beauty or cultural significance etc., and keeping proximity to windy areas, immediately narrows down the number of strategic locations thus, the 72 TW maximum rapidly drops out of reach.

A question that is often overlooked, is to ask where does wind come from? [It, of course, comes from the Sun that heats the ground creating massive convection currents. Thus wind power is solar power in extremely diluted form it is solar power with a 99.9% conversion efficiency loss! Thus on this basis alone we can argue that the footprint of a wind farm can never compete with the obviously smaller footprint area of a solar farm, in the hot regions Wind turbines have a number of problems such as noise, intermittency of supply, sudden surges, unpredictability of supply, turbine blades that snap off in gale force winds, and accumulation of ice on turbine blades. These can, of course, all be managed with appropriate engineering, but in the hot regions, where it makes sense that solar will dominate, economic forces may prevail against wind power. It can be shown that wind power is economically competitive to solar power in cold regions with poor sun levels; see for example, a study carried out in the Newfoundland context where extremely cold conditions dominate [15]. Another point to note is that each wind turbine has bearings, gears, and oil seals that have to withstand enormous forces in high winds. Accordingly, for a typical 1.5 MW wind turbine, as much as of 20 gallons of lubricating oil is required, and often the conditions are so severe that the oil must be specially cooled. Thus if we were to hypothetically supply the world’s energy needs with wind, we would require 40 million gallons of oil per year, assuming we need to replace the sump oil every 5 years. This is tenable with today’s oil production, but will be costly in, say, 40 years time. This calculation is also a warning signal as to why we must urgently replace oil with a suitable renewable source within the next 20 years, as we need the oil for lubricating all the engines of the world. We cannot afford to keep burning oil, as we need it in many diverse industrial applications from lubricants to plastics. For this reason, as wind power is oil-hungry, it is possibly only a medium term solution in cold countries geothermal and hydroelectric power will eventually dominate, and any deficit can be met by importing power from other countries.

5 Energy hydrogen

There are a plethora of methods for producing hydrogen [16] but, when specifically asking the large-scale question of supplying the whole world’s energy needs, many of these options can be eliminated. Take, for example, the electrolysis of ammonia ðNH4Þ leading to nitrogen and hydrogen the obvious questions are: i) from where do we sustainably obtain all the ammonia, and ii) how do we manage the voluminous unused byproduct, in this case, nitrogen? By asking similar questions of every method it is easy to see weaknesses in their viability for world-scale operation. The only option left that passes the test for large-scale viability is the splitting of water into hydrogen and oxygen [17]. The reasons are that: i) water is an option that requires no mining; ii) there are vast supplies of water; iii) the combustion of hydrogen creates water, and so we have a reversible cycle; iv) there are no significant byproducts; and v) the use of extraneous chemicals and exotic materials is minimized. This leads us to the question of how best to split water, and the various options are discussed above. Thermo chemical splitting [18] uses heat to split water into hydrogen and oxygen. The drawback is that temperatures around 2500 C are needed and there are no suitable low-cost materials for containing fluids at that temperature. The operating temperature can be reduced if additives such as sulfuric acid or zinc are introduced, however, efficiencies of only around 50% have been achieved [16] and this is not sufficient to justify the environmental burden of an extra chemical pathway. A recent study of thermal separation of water, using solar energy as the heat source, with thermo acoustics as the means of separating the resulting gases, shows this is 30 times more costly than a solar-driven Sterling generator simply electrolyzing water [19]. Thermal splitting at 800 C using simple iron oxides has recently been proposed, though extensive experimentation has not been carried out as yet [20]. Photo electrolysis [16] can be eliminated as a possibility, as it is essentially a semiconductor solar cell configured to directly produce hydrogen by splitting water, and we have already argued the case against solar cell technology in Section VIII-A. Photo catalytic water splitting is possible [21], though its potential for global scalability is questionable due to the need for exotic transition element catalysts. This leads us to the final remaining option, namely, electrolysis. Commercial water electrolysis systems, at room temperature and pressure, have efficiencies of 56%73% [22]. Proton exchange membrane (PEM) electrolysis can be ruled out, for our purposes as its efficiency is in the 55% range, which is not dramatic enough to justify the use of expensive membrane technology and exotic elements such as iridium, ruthenium, and rhodium as catalysts [23]. Solid oxide electrolysis cells (SOEC) have been demonstrated with efficiencies up to 69%, but again use exotic materials such as yttria stabilized zircon (YSZ) electrolyte and metal doped lanthanum metal oxides [16], [24]. Thus we are left with the final option: alkaline electrolysis that does not use expensive membrane technology, but has about a 10% lower efficiency [16] than PEM electrolysis. The slightly lower efficiency can be compensated by factoring in the nonrecurring cost of more solar dishes, rather than sustaining the recurring cost of continually replacing membranes. Alkaline electrolysis is a current commercial technology, using a ceramic micro porous separator and an aqueous KOH or NaOH electrolyte that, in principle, can be recovered and re-used. The electrodes are usually made of nickel, with the cathode coated in platinum and the anode coated in manganese oxide or tungsten oxide [16]. Platinum is a precious resource, and perhaps the best way forward might be to use a more common metal or alloy instead, and compensate the resultant drop in efficiency (by 10%ou20%) with more solar dishes. We can reduce this efficiency drop in not using platinum, with an increase in efficiency by performing electrolysis on heated water. An increase in water temperature by 50 C can increase efficiency by 10% [25]. Gangly has demonstrated high temperature and pressure electrolysis using cobalt plated anodes [26]. A pinch analysis can be performed to analyze the possibility of heating the water at no extra cost, using available heat from existing solar collectors.

6 Conclusion

Energy will always remain first goal for any nation, but renewable energy are more is an ultimate one. On this chapter we introduced clean energies, their process and challenges. In the next chapter, will detail hydrogen process, myth and safety considerations

chapter2 : Production hydrogen and storage

1 Introduction

Hydrogen, the first element on the periodic table with an atomic number of 1, is truly in a class by itself. It does not belong to any family of elements. Although hydrogen is a non-metal, it is placed on the left side of the periodic table along with the first group alkali metals, but obviously, hydrogen does not belong to the alkali metals family. Hydrogen is the most abundant element in the universe; it is found as interstellar gas and as the chief constituent of main sequence stars. Helium is the other element similar to hydrogen in its simplicity and abundance, and is placed on the same row at the right side of the periodic table. Although helium is a noble gas, and hence it is chemically inert, hydrogen reacts with all sorts of other elements and makes variety of useful compounds. For instance, the bonding of hydrogen with carbon forms the backbone for a vast collection of organic molecules, known as hydrocarbons. Similarly, by bonding with oxygen, hydrogen makes water, the single most important compound on the Earth. Although hydrogen is the most abundant element, it makes up only about 0.14% of the Earth's crust by weight. It occurs, however, in vast quantities as part of the water in oceans, ice packs, rivers, lakes, and the atmosphere. As part of innumerable carbon compounds, hydrogen is present in all animal and vegetable tissue and in petroleum. Even though it is often said that there are more known compounds of carbon than of any other element, the fact is that, because hydrogen is contained in almost all carbon compounds and also forms a multitude of compounds with all other elements (except some of the noble gases), it is possible that hydrogen compounds are more numerous. Elementary hydrogen finds its principal industrial application in the manufacture of ammonia; a compound of hydrogen and nitrogen, and in the hydrogenation of carbon monoxide and organic compounds to make a variety of chemicals and fuels. Hydrogen has also been considered as a potential source of power and transportation and, perhaps in the future, as a source of abundant clean energy. The purpose of this chapter is to provide an overview of hydrogen, its physical and chemical properties, an overview of industrial production, and uses in chemical and energy industries. [27]

2 Some historical events:

In 1766

Henry Cavendish, the British scientist, first identified hydrogen as a distinct element after observing a gas evolved by the reaction of zinc metal with hydrochloric acid. In a demonstration to the Royal Society of London, Cavendish applied a spark to hydrogen gas that yielded water (H2O). This discovery led to his later finding that H2O is made of hydrogen and oxygen.

In 1783

Jacques Alexander Cesar Charles, a French physicist, launched the first hydrogen balloon flight known as Charliere. This unmanned balloon flew to an altitude of 3 km. Three months later, Charles himself flew in his first manned hydrogen balloon.

In 1788

Based on the discoveries of Cavendish, the French chemist Antoine Lavoisier gave hydrogen its name, which was derived from Greek words: “hydro” and “genes,” meaning “water” and “born of.”

In 1800

English scientists William Nicholson and Sir Anthony Carlisle discovered the process of “electrolysis.”

In1838

Swiss chemist Christian Friedrich Schoenbein discovered the fuel cell effect that produced electric current and pure water by combining hydrogen and oxygen gases.

In 1845

Sir William Grove, an English scientist and judge, demonstrated Schoenbein’s discovery on a practical scale by creating a “gas battery.” He earned the title “father of the fuel cell” for his achievement.

In1874

Jules Verne, a French author, prophetically examined the potential use of hydrogen as a fuel in his popular work of fiction entitled The Mysterious Island.

In1889

Ludwig Mond and Charles Langer attempted to build the first fuel cell device using air and industrial coal gas.

In1920

German engineer Rudolf Erren converted the internal combustion engines of trucks, buses, and submarines to use hydrogen or hydrogen mixtures. During this period, British scientist and Marxist writer, J.B.S. Haldane, introduced the concept of renewable hydrogen.

In1952

The United States of America conducted its first nuclear test of a fusion device, or "hydrogen bomb" at Eniwetok in the Marshall Islands.

In1958

The United States formed the National Aeronautics and Space Administration (NASA). NASA's space program currently uses the most liquid hydrogen worldwide, primarily for rocket propulsion and as a fuel for fuel cells.

In 1959

Francis T. Bacon of Cambridge University in England built the first practical hydrogen-air fuel cell. The 5-kW system powered a welding machine. He named his fuel cell design the "Bacon cell." Later that year, Harry Karl Ihrig, an engineer for the AlliseChalmers Manufacturing Company, demonstrated the first fuel cell vehicle: a 20-horsepower tractor. Hydrogen fuel cells, based upon Francis T. Bacon's design, have been used to generate on-board electricity, heat, and water for astronauts aboard the Apollo spacecraft and all subsequent space shuttle missions.

In 1970

Electrochemist John O'M. Bock is coined the term "hydrogen economy" during a discussion at the General Motors (GM) Technical Centre in Warren, Michigan. He later published Energy: The Solar-Hydrogen Alternative, describing his envisioned hydrogen economy in which he explains how cities in the United States could be supplied with energy derived from the sun.

In1973

The OPEC oil embargo and the resulting supply shock suggested that the era of cheap petroleum had ended and that the world needed alternative fuels.

Consequently, the development of hydrogen fuel cells for conventional commercial applications began.

In 1974

The International association for Hydrogen Energy (IAHE) was formed at the Hydrogen Economy Miami Energy Conference (THEME), the first international conference that Prof. T. Nejat Veziroglu of the University of Miami, Florida, organized to discuss hydrogen energy.

In 1976

The International Journal of Hydrogen Energy (IJHE) was established by T. Nejat Veziroglu as its editor-in-chief, and published by Pergamon Press, to provide a platform for hydrogen energy related scientific papers.

In1977

The International Energy Agency (IEA) was established in response to global oil market disruptions. IEA activities included the research and development of hydrogen energy technologies. The U.S. Department of Energy (DOE) was also created during this time.

In 1989

The National Hydrogen Association (NHA) was formed in the United States with 10 members. Today, the NHA has nearly 100 members.

In 1990

The United Nations International Standards Organization (ISO), at the initiative of GustarGrob of Switzerland, established the ISO/TC-197 Committee to prepare the international standards for hydrogen energy technologies.

In 1990

The world’s first solar-powered hydrogen production plant at Solar Wasserst off-Bayern, a research and testing facility in Southern Germany, became operational.

In1994

Daimler Benz demonstrated its first NECAR I (new electric car) fuel cell vehicle at a press conference in Ulm, Germany. 1998 Iceland unveiled a plan to create the first hydrogen economy by 2030 with DaimlereBenz and Ballard Power Systems.

In1999

The Royal Dutch/Shell Company committed to a hydrogen future by forming a hydrogen division. Europe’s first hydrogen fueling stations were opened in the German cities of Hamburg and Munich.

In2000

Ballard Power Systems presented the world’s first production-ready PEM fuel cell for automotive applications at the Detroit auto show.

In 2004

The world’s first fuel cell-powered submarine undergoes deep-water trials (Germany navy).

In2013

Honda unveiled its new FCEV concept hydrogen fuel-cell vehicle at the Los Angeles auto show, promising to market the car initially in Japan and the United States in 2015 followed by European introduction. Chiyoda Corp. plans to build what it describes as the world’s first large-scale power plant fuelled mainly by hydrogen (70%) and natural gas (30%). [28]

3 Physical and chemical properties

Naturally, hydrogen exists in molecular form. It is a colourless, odourless, and tasteless gas. It changes from gas to liquid at a temperature of 252.77 C (422.99 F) and from liquid to solid at a temperature of 259.2 C (434.6 F). It is slightly soluble in water and alcohol. It has the lowest density (0.08999 g/L) of all elements and the ability to rapidly disperse and quickly ascend to the upper atmosphere. Hydrogen is an extremely flammable gas. It burns in air and oxygen to produce water. When mixed with air and with chlorine, it can spontaneously explode by spark, heat, or sunlight. The molecular hydrogen dissociates into atomic hydrogen with a dissociation energy of around 435 kJ/mol. The atomic hydrogen is very reactive. It can bond to other atoms to make either covalent bond or ionic bond. In making covalent bond, hydrogen is unusual, because most atoms confirm to the octet rule, ending up with eight valence electrons, the bonding behaviour of hydrogen follows the duet rule, resulting in just two electrons for bonding. Examples of covalent bonds with hydrogen include water (H_2O), hydrogen sulphide (H_2S), and ammonia (NH_3) as well as the many organic compounds formed on a hydrogen carbon backbone. For making ionic bond, it gains an extra electron to become the negative ion H, or hydride ion. It is then able to combine with a metallic positive ion (cation). Ionic hydrides are convenient sources of hydrogen gas: for instance, calcium hydride, or C_aH_2, is sold commercially and provides a very convenient means of hydrogen generation. The hydrogen gas produced by the reaction of calcium hydride with water can be used to inflate life rafts. The surfaces of metals that do not combine with hydrogen to form stable hydrides (e.g., platinum) catalyse the recombination of hydrogen atoms to form hydrogen molecules and are thereby heated to incandescence by the energy that this reaction releases. Molecular hydrogen exists in two types; ortho and para hydrogen. They differ in the magnetic interactions of the protons due to the spinning motions of the protons. In ortho-hydrogen, the spins of both protons are aligned in the same direction—that is, they are parallel. In para-hydrogen, on the other hand, the spins are aligned in opposite directions and are therefore ant parallel. The relationship of spin alignments determines the magnetic properties of the atoms. Normally, transformations of one type into the other (i.e., conversions between ortho and para molecules) do not occur and orthohydrogen and para-hydrogen can be regarded as two distinct modifications of hydrogen. The two forms may, however, interconvert under certain conditions. Equilibrium between the two forms can be established in several ways. One of these is by the introduction of catalysts (such as activated charcoal or various paramagnetic substances); another method is to apply an electrical discharge to the gas or to heat it to a high temperature. The concentration of para-hydrogen in a mixture that has achieved equilibrium between the two forms depends on the temperature. At 0 K (-273 C), hydrogen presents primarily as para-hydrogen, which is more stable. At the temperature of liquefaction of air(around 80 K or -193 C),21, the orthopara hydrogen ratio is 1:1 and the ratio increases to 3:1 around room temperature. Essentially pure para-hydrogen can be produced by bringing the mixture into21 contact with charcoal at the temperature of liquid hydrogen; this converts all the orthohydrogen into para-hydrogen. The orthohydrogen, on the other hand, cannot be prepared directly from the mixture because the concentration of para-hydrogen is never less than 25%. The two forms of hydrogen have slightly different physical properties. The melting point of para-hydrogen is 0.10 C lower than that of a 3:1 mixture of orthohydrogen and para-hydrogen. At 252.77 C, the pressure exerted by the vapour over liquid para-hydrogen is 1.035 atm compared with 1.000 atm for the vapour pressure of the 3:1 orthoepara mixture. As a result of the different vapor pressures of para-hydrogen and orthohydrogen, these forms of hydrogen can be separated by low-temperature gas chromatography, an analytical process that separates different atomic and molecular species on the basis of their differing volatilities.

4 Hydrogen production

Hydrogen is the most common element on the Earth but it remains combined with other elements and is always found as part of water, biomass and fossil hydrocarbons. Hydrogen gas is currently produced from a variety of primary sources such as natural gas, naphtha, heavy oil, water and coal [29] currently; industrial plants produce about 55 million metric tons of hydrogen globally each year, with its increasing demand of about 5% per year, almost all of which is for captive use in the chemical and refinery industries. Almost 50% of the world hydrogen production comes from the steam reforming (SR) of natural gas, an additional 30% from higher hydrocarbons reforming from refinery-chemical industrial off-gases, 18% from coal gasification, 3.9% from water electrolysis and a very low fraction of about 0.1% from other sources [30] .Almost half of this hydrogen goes into making ammonia a major component of fertilizers, whereas refineries use the second largest amount of hydrogen for chemical processes such as removing sulphur from gasoline and converting heavy hydrocarbons into gasoline or diesel fuel. Many other industries, e.g. methanol, food, metal-lurgy, glass, pharmaceutical consume the rest. Apart from its traditional uses, hydrogen is considered an ideal energy carrier in future energy systems that need to be economically and environmentally sustainable. The possibility of using hydrogen as an alternative energy carrier has intensified the exploration of hydrogen production processes from a wide range of primary sources such as biomass, coal, solar and nuclear. The use of natural gas, whose major component is methane, fails to provide a solution to deal with the huge amount of carbon dioxide emissions (approximately 7 kg CO_2/kg H_2) during the reforming processes. Not only the use of fossil fuels contributes to the greenhouse gases pool but the depletion of fossil resources also threatens sustainable development [31].It is obvious that hydrogen production can be environmentally friendly only if the precursor used to extract hydrogen is renewable. Thus, biomass, a product of photosynthesis, is an attractive alternative to fossil feedstock's as it can be considered as a renewable H_2precursor. CO_2-neutral hydrogen production can be achieved by the conversion of biomass via gasification [32]. pyrolysis of bio-oils [33], SR of biomass-derived higher alkynes and alcohols [34].and aqueous phase reforming (APR) of oxygenated hydrocarbons [35].

4.1Steam reforming of methane and light hydrocarbons

The SR process involves three reactions, namely, the splitting of hydrocarbons with steam (Eqn (1), the water-gas shift (WGS) (Eqn (2)) and the formation of methane (Eqn 3)

$$C_nH_m + n\,H_2O \rightarrow n\,CO + (n + m\backslash 2)H_2 \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

$$CO + 3H_2 \rightarrow CH_4\ H_2O \qquad (3)$$

It is emphasized that the H:C atom ratio of the raw feedstock is an important parameter characterizing the SR process. The higher this ratio is the lower carbon dioxide emission is formed. For methane, H:C ratio is 4, which results in the lowest CO_2 emissions, about 7 kg CO_2/kg H_2. The reaction products are controlled mainly by thermodynamics, which favours the production of methane at lower temperatures (approximately 623 K) and of hydrogen at higher values (approximately 1273 K). The SR catalysts usually contain nickel as the major metallic component. The noble Group 8 metals are also active in the reforming reaction but the cost makes them prohibitive. The catalytic activity depends on the metal area, and their properties are dictated by the severe operating conditions such as temperatures in the range 700-1250 K and steam partial pressures of up to 30 bar. The activity of the catalyst is not, in general, a limiting factor. Thus, a typical nickel catalyst is characterized by a turnover frequency of approximately 0.5 s^{-1} at 723 K under conditions approaching industrial practice, which corresponds to CH4 conversions around 10%. The principal barrier is the equilibrium conversion which determines very high conversions only at temperatures above 1170 K. As a consequence of the strong mass and heat transfer limitations, classical reformers are limited by the effectiveness factor of pelletized catalysts, which is usually less than 10%, whereas kinetics is rarely the limiting factor [36]. The heat efficiency of hydrogen production by the SR of methane process on an industrial scale is 80-85% [37].

The traditional SR process basically consists of several units Figure 2.1. feed gas preheating and pre-treatment units, performer unit, reforming unit, high- and low-temperature WGS units and hydrogen purification unit. A conventional methane steam reformer is quite large (approximately 450,000 Nm3 H2/day) and operates with a contact time of the order of 1 s. In the performer, all high hydrocarbons are converted directly into C1 components (methane and carbon oxides) at a low temperature range, typically from 673 to 823 K. The products from performer could be heated to temperatures up to 1073 K, reducing the risk of carbon formation from thermal cracking of the fuel before it reaches the reforming catalyst bed. The performing catalyst is especially prone to carbon deactivation from the low operating temperature. Specially precipitated high nickel-loaded catalysts (Ni ¼ 20e30 wt%) with supports with alkaline properties (MgO =60-70 wt%) and high surface area are used in the performing process.

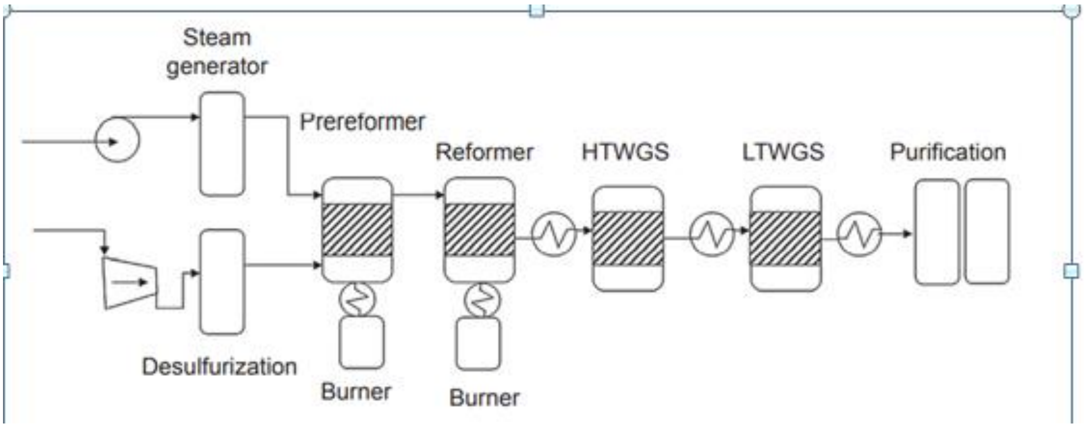


Figure 2-1: flow diagram corresponding to conventional steam reforming of the methane hydrocarbons

The carbon monoxide obtained after the reforming could be converted to additional hydrogen by means of the WGS reaction. The WGS reaction is run in two catalytic stages: high temperature shift (HTS) and low temperature shift (LTS). These two units, which are placed downstream of the reformer, ideally reduce the CO content to less than 0.5% vol. In industrial application, the conventional catalyst formulations employed are Fe_2O_3-Cr_2O_3 and Cu-ZnO-Al_2O_3 for the HTS and LTS units, respectively [38]. For typical reformate streams (8-10% vol CO), the HTS reactor operating at near equilibrium (623-693 K) reduces the CO level to about 4% vol, whereas the LTS working at 453-613 K achieves 0.4-0.8% vol CO.

The H2-rich stream produced after WGS still contains some contaminants, i.e. unconverted CH4, some minor mounts of CO, etc. All of them are traditionally removed in a pressure swing adsorption unit, thus a purified H2 stream with a typical purity of 99.99 vol% is produced. In the pressure swing adsorption units, gases other than hydrogen coming from the reformer are adsorbed at elevated pressure on activated carbon or molecular sieves. These none-H2-containing gases are desorbed by expanding the absorber tank to nearly atmospheric pressure and then returned to the reformer reactor as auxiliary fuel.

4.1.1 Catalysts and mécanisme

Most SR catalysts are based on a nickel phase deposited on suitable carrier such as Al_2O_3, $MgAl_2O_4$ and ZrO_2. Cobalt and noble metals are also active phases in the SR reaction but their costs make them prohibitive for large-scale operation. A detailed description of the nature of the active phase, catalyst supports, promoter effects and strategies employed in bibliography to prepare highly active catalysts for the SR reaction can be found in our previous works [34]. The catalytic activity of reforming catalysts depends on the surface area of the supported metal phase and their properties are dictated by the high temperatures, usually above 1023 K required to run the reaction. As a matter of fact, the activity of the SR catalysts is not a limiting factor. The SR is a mass-transfer limited reaction at the high working temperatures needed [39]. Because the intrinsic activity of the catalyst is proportional to its nickel surface area, the key criterion for designing Ni reforming catalysts is maximizing the heat transfer at low pressure drop. The mechanism of methane SR reaction on supported Ni catalysts has been studied in some detail [40]. Although there have been many controversies, recent theoretical and experimental contributions have been formulated to derive a mechanism for SR of methane on Ni. From these results, it was established that the methane SR is a structure sensitive reaction and that under-coordinated Ni surface sites, i.e. corners and edges, are more active than close-packed Ni sites. It was also demonstrated that the rate-limiting step of the reforming reaction is the activation of C-H bonds of CH_4 molecule. According to these studies the following mechanism for the formation of syngas from methane was proposed:

$$H_2O_{(g)} \rightarrow O_{(a)} + H_{2(g)} \qquad (4)$$

$$CH_{4(g)} + 2^* \rightarrow CH_3-^*_{(ad)} + H-^*_{(ad)} \qquad (5)$$

$$CH_3-^*_{(ad)} + 2^* \rightarrow Ch_2-^*_{(ad)} + H-^*_{(ad)} \qquad (6)$$

$$CH_2-^*_{(ad)} +^* \rightarrow CH -^*_{(ad)} + H-^*_{(ad)} \qquad (7)$$

$$CH-^*_{(ad)} + {}^* - O_{(ad)} \rightarrow^* - CO_{(ad)} + H-^*_{(ad)} \qquad (8)$$

$$CO-^*_{(ad)} \rightarrow C0_{(g)} + {}^* \qquad (9)$$

$$2H-^*_{(ad)} \rightarrow H_{2_g} + 2^* \qquad (10)$$

Where * denotes a Ni surface atom. According to this mechanism, H2O reacts with surface Ni atoms, towards surface carrier adsorption, providing adsorbed oxygen and gaseous hydrogen. The mechanism proposed for methane SR (Eqn(4).(8).(10)) is also generally accepted for the reforming of higher aliphatic hydrocarbons. However, hydrocarbon adsorption needs a dual site to split the C-C bond (Eqn(11).(12)).

$$R - CH_2 - CH_{2(g)} + 2^* \rightarrow R - CH^* - CH^*_{2_a} + H_2 \qquad (11)$$

$$R - CH^* - CH^*_{2(a)} \rightarrow R - CH^*_{(a)} + {}^*CH_{2(a)} \qquad (12)$$

In the course of the SR reactions, carbon formation usually takes place in the form of fibres or whiskers. These carbonaceous deposits accumulate progressively on the catalyst surface result with subsequent drop in the activity of the catalyst and in some cases may cause partial or complete blockage of the reformer tubes. Carbon formation from methane includes two kinds of carbonaceous deposits: (1) elemental carbon formed directly from methane decomposition Eqn (13) or (2) CO disproportionate Eqn (14):

$$CH_4 \rightarrow C + 2H_2 \qquad (13)$$

$$2CO \rightarrow C + CO_2 \qquad (14)$$

Carbon formation on the catalyst surfaces depends to a large extent on the reaction conditions and surface properties of the catalyst [39][40]. Whisker is the most common form of carbon produced on the metal surface during steam methane reforming (SMR) reactions [34].

The mechanism involved in whisker formation includes first the dissociation of adsorbed CH_4 or CO on the metal surface, yielding C atoms that dissolve within the metal particle; then carbon diffuses through the particle and nucleates into the filament at the rear interface. These carbon whiskers have high mechanical strength and the catalyst particles might well be destroyed when the whiskers hit the pore walls of the substrate. Given that the formation of carbon on nickel surfaces takes place in ensembles of specific sites [41].and by means of surface metal carbide formation, several approaches can be followed to minimize coke formation on Ni or other metal surfaces: (1) controlling the number of surface Ni sites in a given ensemble (ensemble size control) [42], (2) modification of the electronic properties of the active metals limiting the possibility of metal carbide formation by alloy or surface compound formation [43] ,or by means of changes in metal-support interactions and (3) enhancement of steam adsorption using carefully engineered supports with the addition of alkali (K or Mg) or lanthanide oxides [44].

4.2 **Alcaline electrolysis**

Alkaline electrolysis is considered a mature technology with many decades of commercially available products for the production of hydrogen gas. This industry grew substantially during the 1920s and 1930s. Alkaline electrolysis can be described as the use of an electrical current passing through an electrolysis cell causing the decomposition of water to generate hydrogen gas on the cell’s cathode. In an electrolysis cell two electrodes containing an electrocatalyst, separated by a physical barrier, a polymeric diaphragm which only allows the passing of ions from one electrode to another, are connected to a current source. Each cell will have a high specific active area due to its porous structure and will produce hydrogen gas at the cathode while oxygen will be produced in the anode. The electrodes are in contact with an electrolyte which provides OH- ions, from a 20%–30% solution of potassium hydroxide that completes the electrical circuit. In theory, 1kg of hydrogen would need a little less than 40kWh of electricity. Although theoretical water decomposition voltage is 1.23V (which corresponds to a theoretical dissociation energy of 286 kJ/mol or 15.9 MJ/kg at 25°C), in practice this voltage goes normally to around 2V per cell, while the total applied current depends on the cell's active area, and on the electrolyzer configuration (bipolar or unipolar). In the first case current densities (A/cm2) are higher than in unipolar configurations. There exist certain advantages in bipolar systems as they can operate under pressurized conditions, reducing or facilitating a compression stage. Higher current densities and generally a smaller foot-print are other positive characteristics of bipolar electrolyzers. As electrodes are placed closer, voltage drop from ohmic resistances are minimized saving in energy costs.

As mentioned earlier, there exist other electrolyzers that use a solid acid electrolyte based on an ionic conducting electrolyte. Those will not be treated in this document/section. Electrode and global reactions in an alkaline electrolyzer are as follows

Cathode : $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (15)

Anode : $2OH^- \rightarrow {}^1/_2\, O + H_2O + 2e^-$ (16)

Globale réaction : $2H_2O \rightarrow H_2 + {}^1/_2\, O_2$ (17)

The operating temperature is typically around 80-90°C producing pure hydrogen (>99.8%). Higher temperatures are being also used as the electrolysis of water steam decreases electricity costs. Pressure is another characteristic operating condition which goes from 0.1 to around 3MPa. As with temperature, higher pressures help to decrease energy costs particularly as this generates high pressure hydrogen lowering compression energy when hydrogen will be stored or dispatched as a pressurized gas. Some approaches of cero pressure have been proposed generating then low pressure (about 40 bar) hydrogen without any mechanical compressor. An approach to pressurized electrolyzes sometimes comprises a first stage where hydrogen is generated at about 200-500psi (13.8-34.5 bar) followed by a mechanical compression second stage to upgrade it to 5000psi (3447 bar). Commercial units often use nickel-coated steel in their electrodes but other proprietary materials are associated too to some products. The efficiency of alkaline electrolysis is about 70% LHV (Lower Heating Value), where hydrogen cost is associated to electricity costs, one of the main technological challenges along with the wholesale manufacture which also needs to improve in order to reach technology costs goals for competitiveness. Approximately a little less than 1 liter of de-mineralized water is needed to generate 1Nm3 of hydrogen. Once produced, hydrogen goes through a series of conditioning stages as seen in figure below: The main goal is to eliminate traces of KOH, water and oxygen. In the system diagram shown the transformer/rectifier plays an important role in converting A.C. current to D.C. current which is actually the type of current involved in the electrochemical process of electrolysis. As mentioned earlier, the actual cost of hydrogen will be dependent on the source of electricity. Therefore, renewable energy, especially as D.C. electricity, can greatly contribute to a more competitive hydrogen cost. It is reported also that electrolysis is better respondent to a load-following condition compared to other hydrogen production methods (e.g. MSR), making renewable energy related hydrogen a more suitable energy integrated system. [45]

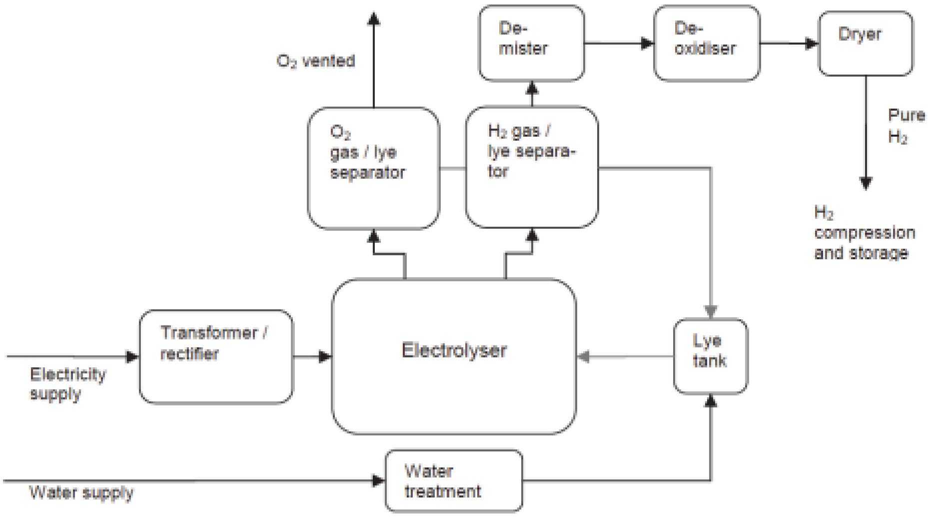
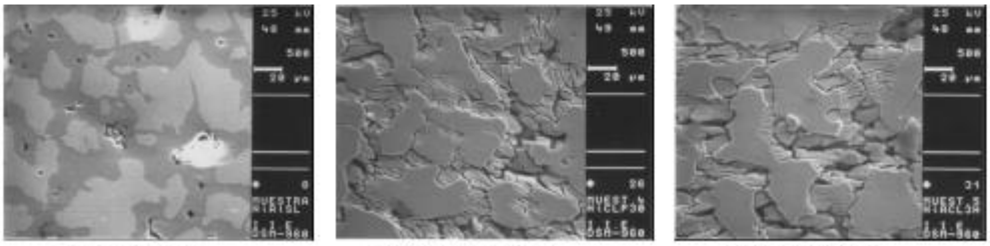


Figure 2-2 : Schematic diagram of alkaline electrolyzer components [46]

4.2.1 Alkaline electrolysis components:

4.2.1.I Electrodes

One of the materials most used in the hydrogen industry for alkaline electrolysis is nickel. This is due to its excellent catalysts properties and its corrosion resistance at the high pH values of KOH electrolyte in particular at the highly imposed anodic potential for the oxidation reaction. Often Pt alone or together with Ni, is used in commercial products improving electrode kinetics performance but this increases the overall costs of the unit. Electrodes are manufactured so that they show a large electro active area, therefore porous electrodes are normally made to produce large density currents and better hydrogen production rates. One type of nickel electrode material used is Ni Raney or skeletal Ni, a material developed almost 100 years ago as a catalyst for hydrogenation of oils. Skeletal Ni is prepared from a Ni-Al alloy at specific concentration depending on the desired properties. This alloy is then leached in an alkaline solution to dissolve an aluminum containing phase leaving behind a porous structure. During the leaching process there is production of hydrogen which is said to remain in the porous making the resulting material pyrophoric and difficult to handle. Also the remaining aluminum can act as a trap for hydrogen as this metal is known to adsorb hydrogen molecules, which dissociate to produce hydrogen atoms within the metal-. This hydrogen is believed to serve as a hydrogen- “prepared” surface for the further hydrogen evolution process at the cathode regardless of the reaction mechanism. The following figures show a microstructure of the Ni-Al alloy and its typical phases formed after alloying (a) and after the leaching process (b and c).[47]



a) before leaching b) leached 30 minutes c) leached 3 hours

Figure 2-3 SEM micrographs (500X) showing microstructure of Nickel Raney electrodes and the leaching time effect in alkaline solution {47]

As nickel oxidizes in an alkaline solution forming oxides and hydroxides of the metal, it is also believed that most of the catalyst properties in Ni electrodes come from those phases. For example, Subbaraman et al. combined nickel oxide and platinum to produce a more effective catalyst than either component alone. The authors propose a mechanism in which nickel helps to cleave the O-H bond while platinum directs the separated H intermediates to form H2. Section 3 reviews some literature on different electrode systems researched in the last few years in order to make more effective and economically attractive electrodes.[48]

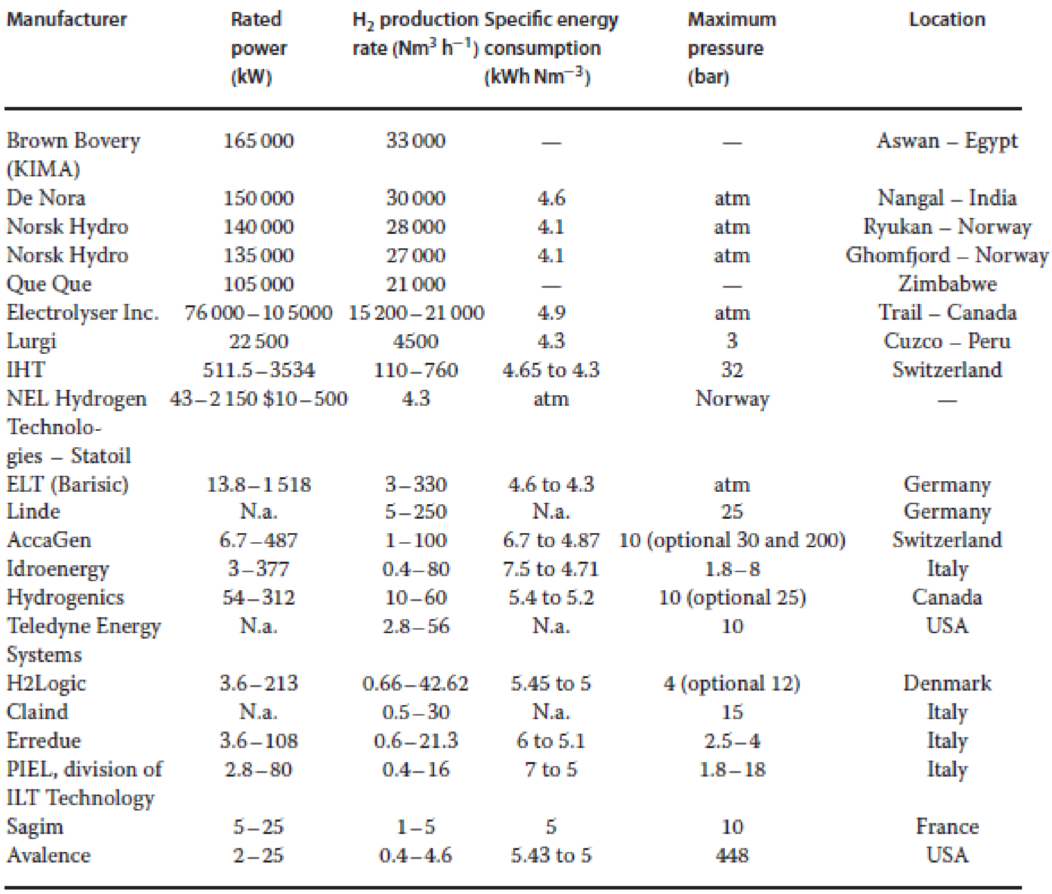
4.2.1.II Electrolyte

As mentioned earlier KOH solutions are used in alkaline electrolysis. This electrolyte is contained in a closed circuit to avoid contact with CO2 from the atmosphere that could impose an adverse technical challenge due to the precipitation of carbonates formed. The KOH concentration is very important as it determines the ionic conductivity that should remain high in order to avoid the use of higher voltages from ohmic losses. These losses could increase the energy use and therefore the hydrogen cost.[45]

4.2.1.III Diaphragm

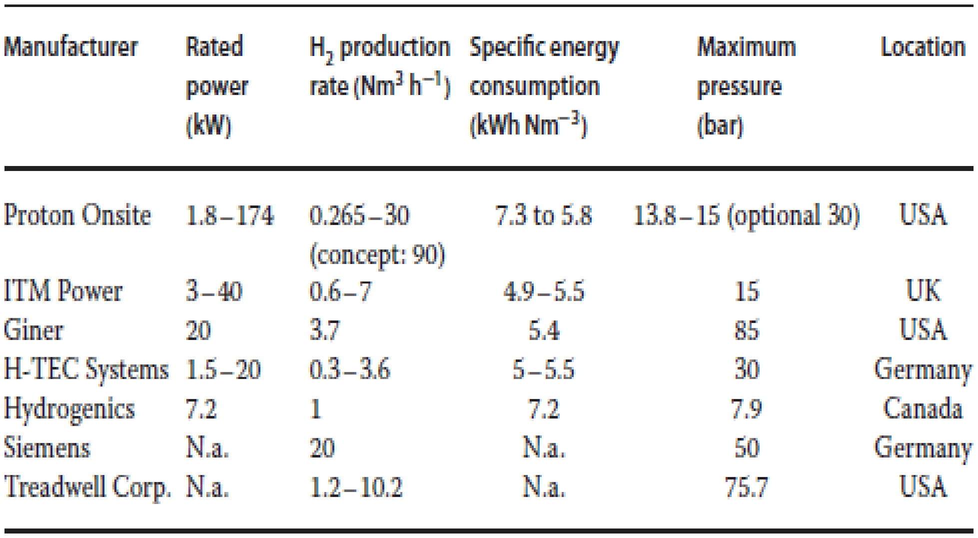
In alkaline electrolysis a diaphragm is a separator which should keep a good ionic conductivity while effectively separating hydrogen and oxygen gases generated at the cathode and anode sides respectively. It typically consists of a matrix porous material which should chemically stand (and contain) a corrosive environment (~25% KOH solutions) at relatively aggressive temperatures (~85°C). It should also be mechanically strong to withstand changes in dimensions (compression) due to stresses associated to structural design and due to temperature changes. Although asbestos have been used for many decades, alternative polymeric matrixes are preferred by main developers due to the potential asbestos exposure health risks. Along with the economics in the selection of materials, efficient operation needs to be ensured by materials with low gas permeability, low ionic resistance (but high electronic resistance). The effective thickness, i.e. the product of Mac Mullin number and thickness of the matrix material, is normally determined while selecting diaphragms as it better represents its effectiveness. The Mac Mullin number, defined as the ratio of the specific resistivity of the electrolyte-saturated matrix material to the resistance of the same volume of electrolyte, can be obtained using Electrochemical Impedance Spectroscopy (EIS) measurements. [45] From the technical point of view there have been corrosion problems by the use of alkaline solutions in recent international projects, which turned into down time of the equipment. Nevertheless, this could be more a good engineering practice issue (for example materials selection) than a technological problem. [45]

Table 2-1 : Realized alkaline water electrolyses manufacturers[49]



Manufacturer	Rated power (kW)	H_2 production rate ($Nm^3 h^{-1}$)	Specific energy consumption ($kWh Nm^{-3}$)	Maximum pressure (bar)	Location
Brown Bovery (KIMA)	165 000	33 000	—	—	Aswan – Egypt
De Nora	150 000	30 000	4.6	atm	Nangal – India
Norsk Hydro	140 000	28 000	4.1	atm	Ryukan – Norway
Norsk Hydro	135 000	27 000	4.1	atm	Ghomfjord – Norway
Que Que	105 000	21 000	—	—	Zimbabwe
Electrolyser Inc.	76 000–10 5000	15 200–21 000	4.9	atm	Trail – Canada
Lurgi	22 500	4500	4.3	3	Cuzco – Peru
IHT	511.5–3534	110–760	4.65 to 4.3	32	Switzerland
NEL Hydrogen Technologies – Statoil	43–2 150 $10–500	4.3	atm	Norway	—
ELT (Barisic)	13.8–1 518	3–330	4.6 to 4.3	atm	Germany
Linde	N.a.	5–250	N.a.	25	Germany
AccaGen	6.7–487	1–100	6.7 to 4.87	10 (optional 30 and 200)	Switzerland
Idroenergy	3–377	0.4–80	7.5 to 4.71	1.8–8	Italy
Hydrogenics	54–312	10–60	5.4 to 5.2	10 (optional 25)	Canada
Teledyne Energy Systems	N.a.	2.8–56	N.a.	10	USA
H2Logic	3.6–213	0.66–42.62	5.45 to 5	4 (optional 12)	Denmark
Claind	N.a.	0.5–30	N.a.	15	Italy
Erredue	3.6–108	0.6–21.3	6 to 5.1	2.5–4	Italy
PIEL, division of ILT Technology	2.8–80	0.4–16	7 to 5	1.8–18	Italy
Sagim	5–25	1–5	5	10	France
Avalence	2–25	0.4–4.6	5.43 to 5	448	USA

Table 2-2 :Main PEM water electrolyses manufacturers[49]



Manufacturer	Rated power (kW)	H_2 production rate ($Nm^3 h^{-1}$)	Specific energy consumption ($kWh Nm^{-3}$)	Maximum pressure (bar)	Location
Proton Onsite	1.8–174	0.265–30 (concept: 90)	7.3 to 5.8	13.8–15 (optional 30)	USA
ITM Power	3–40	0.6–7	4.9–5.5	15	UK
Giner	20	3.7	5.4	85	USA
H-TEC Systems	1.5–20	0.3–3.6	5–5.5	30	Germany
Hydrogenics	7.2	1	7.2	7.9	Canada
Siemens	N.a.	20	N.a.	50	Germany
Treadwell Corp.	N.a.	1.2–10.2	N.a.	75.7	USA

5 Utilization hydrogen

Hydrogen was mostly used as a buoyant gas, then as a fuel-gas constituent made from coal. Today, it is used mainly as a chemical agent in petroleum refining and in the synthesis of ammonia and methanol. Most of the hydrogen produced nowadays is manufactured from natural gas and naphtha. Low natural gas and petroleum prices caused coal to be displaced, but the situation in recent years has changed and coal use will be revived as the case may be, in combination with nuclear heat. Solar-Hydrogen Energy Systems More than 98% of hydrogen produced is low purity (lower than 97% pure). The worldwide production, thus the utilization, has increased more than one thousand times the quantity compared to that of forty years ago. Approximately 70 million m3 of hydrogen were produced in 1938 and more than 250 billion m3were consumed in 1974. The utilization of hydrogen is primarily as a chemical in ammonia manufacture, methanol manufacture, petroleum refining, production of foodstuff, metal working, etc. The main uses in the world are shown in Table2.3 Whenever hydrogen is produced from water by any method, oxygen is evolved at the same time. Water would be the feedstock for hydrogen production in the near future. Then the utilization of oxygen would become important. Table 2.4 shows the total utilization of oxygen all over the world in 1972. In this section, a concise review will be given about the utilization of hydrogen today and tomorrow [50].[51]

Table 2-3: Total utilization of hydrogen in the world in 1974 (unit is 108m3)

Ammonia 1 synthesis	Petroleum refining	Methanol synthesis	Miscellaneous	Total
1.370	**750**	**236**	**141**	**2.497**

Table 2-4 : Total utilization of oxygen in the world in 1972 (unit is 108m3)

Iron and Steel	Miscellaneous	Total
336	**224**	**560**

5.1**Medium and advising system**

In the advanced energy systems described in the section 1.1, we have mentioned the important roles of hydrogen which convert hydrogen to electricity, and vice versa. The conversion implements will be the fuel cell, combustion-driven generator, hydrogen fueled MHD generation. All of these installations are not realized yet in practical uses but have been investigated only experimentally. There is no doubt that hydrogen is able to effectively drive those, however, their economical implementation is not ensured yet. In the developed countries, technologies of water electrolysis and of fuel cell have been actively studied. IEA (International Energy Agency, a union of 19 developed countries) has adopted an effective water electrolysis process under high pressures of around 20~30 atm and temperatures around 120~150°C as a common project to be developed cooperatively. The fuel cell was a key implement in TARGET (Team to Advanced Research for Gas Energy Transformation) project in U.S.A., Canada and Japan. Even in the present electric utility system, hydrogen can be used to match electrical generation capability to the demands of customers. This is called peak shaving and plays an important role in the economical aspect as was mentioned in the section 1.1. Hydrogen is used not only in the energy system but also in electrical generation, electrical energy conversion systems. It is a coolant for large generators, motors and frequency changing equipment circulating in a closed gas circuit. Though this is a closed recalculating system, consumption due to losses is estimated at about 30 Z/dayMW. Generators with capacity more than 40MW are usually equipped with hydrogen coolant. People would burn hydrogen fuel someday for heaters and for cooking. A novel property of hydrogen fuel that gives it a marked advantage over other fuels is its Introduction - a Review of the Scope ability to burn with air when in contact with a catalyst. A low-temperature burner is a ceramic plate with porosity about 70%. The internal surface of the plate is coated with a catalyst. The highest activity is found in metals of the platinum family such as Pt, Pd and Ir. The burner can be operated even below 100°C, so that brand new style of cooking would be invented.

5.2 Chemical feed stock

As is shown in Table 2.5, the largest use of hydrogen, today is for ammonia synthesis. Hydrogen from naphtha or natural gas combined with nitrogen from air yields ammonia fertilizer. The next largest use is for petroleum refining such as hydro treating, hydrodesulphurization, hydro-fining, hydro cracking, hydride alkylation and catalytic reforming. This basically means an artificial promotion of the trend toward the direction with arrow. Methanol synthesis is the third largest use of hydrogen. Methanol is usually made from methane gas by steam reforming and is used chiefly as a solvent and precursor in the manufacture of plastics, resin and organ chemicals.

Besides this enormous consumption of hydrogen, there is a broad spectrum of miscellaneous uses of hydrogen. Chemical hydrogenation includes the processing of the edible organic oil from soybeans, fish, cotton seed, corn, peanuts and coconuts. Soap and animal food are produced from edible tallow and grease by hydrogenation. To manufacture certain drugs, hydrogen is extensively used by pharmaceutical companies [48]. Hydrogen is also a feedstock in organic chemical synthesis leading to production of nylon and polyurethane. Hydrogen is really an indispensable chemical feedstock in producing subsistence commodities.

5.3**Hydrogen as ion agented of martials manufacturing**

Hydrogen can serve as a reducing agent and the most prominent application appears to to be iron ore reduction. A variety of direct reduction of iron ores without coke has been carefully studied for a long time. These use hydrogen, carbon-monoxide and carbon in a combination. The reason for the development is due to the following:

1) a wide range of fuels including natural gas can be used. The historical usage of fuel for metallurgical process has started from carbon, coal, which would change to mixture gas of CO, H2 and C. The merit is mostly to avoid the use of high grade coal and coke, and to avoid some of the attendant environmental problems.

2) The size of plants could be economically small (50,000 ton/year).

3) Improvement of output and economics of electric furnace. A hydrogen-nitrogen reducing atmosphere (NH) is often used to prevent oxidation in annealing process of ferrous metals. This atmosphere can be used not only for annealing and heat treatment of nonferrous metals but is also used for the refining process to recover non-ferrous metals such as tungsten, molybdenum and magnesium. A reducing atmosphere of pure hydrogen is used in tungsten processing when oxide compacts are sintered. The molybdenum trioxide is reduced in a furnace with hydrogen at about 1,000°C to produce metal powder. This powder is formed into a sintered rod in a hydrogen atmosphere. Magnesium chloride can be electrolyzed or magnesium oxide can be thermally reduced. In both cases hydrogen gas is consumed. Tanaka et al. [54] have studied the direct reduction of sulfide ores. To prevent oxidation of materials at high temperatures (above 400°C) in brazing process of vacuum tubes, light bulbs and other electronic equipment, hydrogen gas is used. Crystal growing needed to produce semiconductors, Ge, Si, etc., also requires hydro- Solar-Hydrogen Energy Systems

gen. An interaction between the hydrogen energy systems and the computer world will thus be strengthened in time. Hydrogen is employed in uranium extraction and processing, and for corrosion control in nuclear reactors.[53]

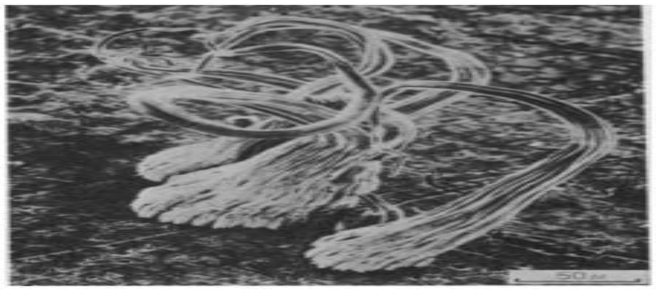


Figure 2-4 : Scanning electron micrograph of silver fibers resulting from reduction of silver sulphide with hydrogen at 500°C [52].

5.4Transportation

Hydrogen fueled piston engine has been studied since the 1930's in connection with airship developments. It is now actually used in a 21-passenger bus [55] and many experimental hydrogens fueled cars have been driven. The R &D of the hydrogen fueled engines has increased a great deal, Hydrogen has very wide limits of flammability when mixed with air (4%~76% of H2), which enables an engine to operate with the mixture far from the stoichiometric composition of 29.6%. Disadvantageous aspects of the engine are tendencies to knock because of its high flame speed and to back fire, which can be eliminated if a mixture is adjusted to contain at least 25% excess air. [53]

6 Hydrogen storage state of art

Storage is a challenging issue that cuts across production, delivery and end-user applications of hydrogen as energy carrier. It constitutes a key enabling technology for the realization of a hydrogen-powered economy**.** Hydrogen can be stored in gaseous form (compressed gas), as a liquid (20K or –253$_o$C) and also in solid media. The first two methods are rather established technologies with several limitations [56] the most important of which is their energy intensive character. Hydrogen solid-state storage, still at its infancy, appears as a possible attractive alternative. This is particularly due to its improved safety and volumetric energy density. Nevertheless, if this solution is chosen there are penalties to be paid in terms of weight efficiencies, thermal management and up-scaling. Intense research is ongoing to overcome the limitations of existing hydrogen storage technologies and to develop viable solutions, in terms of efficiency and safety. The section that follows gives a brief summary of the state-of-the-art of hydrogen storage technologies concentrating on the most promising storage solutions for the short and medium term (2020), depending on the application. It also presents highlights of the main research and development programmers currently running on hydrogen storage related issues, throughout the world.

6.1Storage in gaseous forme

This is currently one of the simplest, most common and efficient storage technologies in use. High-pressure hydrogen is stored in thick-walled tanks (mainly of cylindrical orquasi-conformable shape) made of high strength materials to ensure durability. The storage tank design, which is based on classic deterministic engineering approaches, is not yet optimized: the tanks are actually over-sized; there is inefficient use of material and a rather poor assessment of the pressure vessel lifetime [57], [58].According to the European Integrated Hydrogen Project EIHP [referencewww.eihp.org], which is leading the development of global regulatory standards for hydrogen testing and certification of hydrogen refueling infrastructure components and systems, compressed gas hydrogen storage vessels can be classified in four types as:

Type I: all metal cylinder;

Type II: load-bearing metal liner hoop wrapped with resin-impregnated continuous filament;

Type III: non-load-bearing metal liner axial and hoop wrapped with resin impregnated continuous filament;

Type IV: non-load-bearing non-metal liner axial and hoop wrapped with resin impregnated continuous filament.

The most advanced lightweight storage system for the case of compressed gas consists of a vessel, which is actually an advanced composite tank using a non-load-bearing metallic (Type III) or plastic (Type IV) liner axial and hoop wrapped with resin impregnated continuous filaments Figure2.5. These pressure vessels are attracting most of the interest of the scientific community. Their structure is based on two fundamental components: the liner, essentially a barrier for hydrogen permeation and the composite structure that ensures the mechanical integrity of the tank. Research is directed towards the development of new methodologies for reliability design and safety qualification of these high-pressure storage systems. Also, efforts are concentrated on the extension of these techniques to the next generation of compressed hydrogen storage systems: tanks with complex shapes. [57].

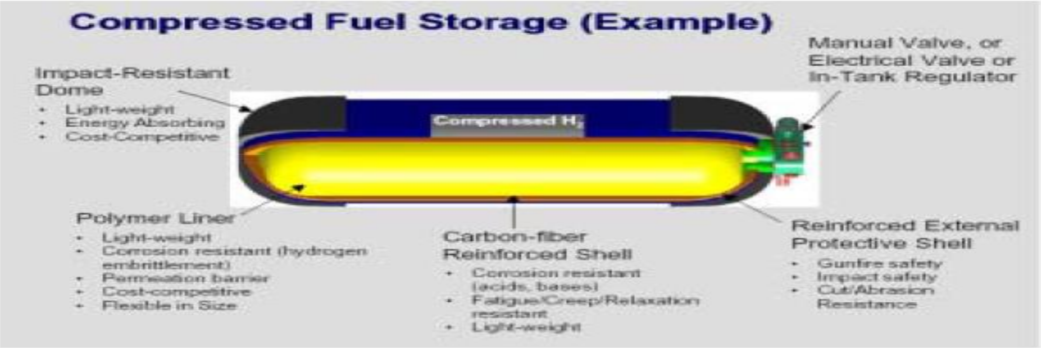


Figure 2-5: Schematic of a compressed gas storage tank and its components [56]

There are some European companies working in this area mainly using their experience from compressed natural gas developing compressed gas hydrogen composite tanks. Some examples are: Dynetek GmbH a subsidiary of Dynetek Industries working on Type II cylinders with stainless steel liner; Composites Aquitaine (EADS group) in France; Faber in Italy using metallic liners; CEA and Ullit in France, and also COMATGmbH in Germany who are developing Type IV cylinders [60]. Japan is not actively involved in R&D programmers on compressed gas storage. However, several Japanese car manufacturers such as Toyota, Honda, Nissan and Suzuki are launching pre-series ofFuel Cell Vehicle fleets equipped with compressed gas tanks at 350 bar designed by Dynetek Industries Ltd. and Quantum Technologies. These are companies linked to car manufacturers actively involved in the research and development on Fuel Cell Vehicles (FCV) [16]. Dynetek Industries have recently reported that their latest high-pressure hydrogen storage cylinders have been tested to 825 bar [59]. These cylinders will be used for storing hydrogen for stationary applications. According to the manufacturer, they have a nominal storage capacity of 170 liters (water content), a service pressure of825 bar and a maximum fill pressure of 1094 bar. They consist of a thin-walled liner made from aerospace-grade aluminum, they are seamlessly formed, with no welds or other bonding points. This method, as claimed by the manufacturing company, promises good sealing performance of the liner. Quantum Technologies under its partnership with General

Motors recently claimed having designed a 700 bar composite tank allegedly increasing to 270 km the driving range of hydrogen-powered fuel cell vehicles. This is a60-70% improvement, compared to an equivalent-sized 350 bar system, with there fueling process taking less than 5 min. It is noted that for large commercialization a480-560 km range is required [60]. This system was approved by TÜV, and it is said tobe validated according to the EIHP.

6.2 **Storage in liquid forms or media**

Hydrogen in liquid form has a considerably higher energy density than in its gaseous form, making it an attractive storage medium. In terms of application, liquid hydrogen and the enabling technology have already been used in space (Space Shuttle, Arianne) but also in military aircrafts. Considering surface transport, a number of cars running with hydrogen in newly designed vessels with losses by evaporation to below 1.5mass% per day have been developed and tested. Also, automated liquid-hydrogen filling stations have been built [62].This hydrogen storage technology is rather effective but has disadvantages, mainly the energy required to liquefy the gas and the strict control needed on the container temperature stability to avoid any risk of overpressure. It also requires cryogenic vessels and suffers from hydrogen losses through evaporation from the containers, particularly the smaller ones (they have a larger surface to volume ratio than large containers, hence larger losses of hydrogen). The continuously evaporated hydrogen may be catalytically burnt with air in the overpressure safety system of the container or even collected again in a metal hydride. The cryogenic vessels used to store liquid hydrogen, sometimes also called cryostats, are metallic double-walled vessels with insulation, sandwiched between the walls. Tominimise if not eliminate thermal losses, effects of thermal radiation; thermal convection and thermal conduction have to be taken into account when designing the vessels Figure2.8 [61]. The inner vessel that contains the cryogenic hydrogen is insulated with a multi-layered material with spacers between each layer acting as thermal barriers. This inner vessel is mounted within the outer vessel by means of specially designed internal fixtures. The resulting volume between the two vessels is evacuated to avoid possible heat leaks (‘vacuum super insulation’) by thermal convection. Deep knowledge of cryogenics is required to properly design and select the materials for the internal fixtures of the vessel/tube system for injecting and extracting the hydrogen, in order to minimize heat leaks by thermal conduction.

The complex design of a liquid hydrogen vessel system is schematically illustrated in Figure 18. Cryogenic storage because of the low working pressure compared to high-pressure storage systems, has a great potential to reduce weight by using new composite materials with enhanced performance. With such systems, specific energy storage mass similar to conventional fuel tanks, can be achieved. These designs will meet the higher requirements regarding environmental conditions and vehicle safety but also cost effectiveness for subsequent series production. Taking into account market constraints, development of composite tanks may yield cost effective materials and processes [58]. Even though there is so much caution on the design part of these storage tanks to ensure protection from unwanted heat entry, cryogenic liquids and therefore hydrogen do evaporate ("boil-off") due to the impact of heat on the tank system. This phenomenon cannot be avoided, but only minimized. If a vehicle equipped with such a system is not used for a rather short time (about 3 days), the tank pressure rises as a result of the heat ingress. A critical pressure value is finally reached that triggers unacceptable hydrogen evaporation losses. This situation may improve by using a re-cooling system (developed by Linde AG) that allegedly minimizes evaporation losses. As a result, the critical time before boil-off occurs may be extended (morethan12days) [61]

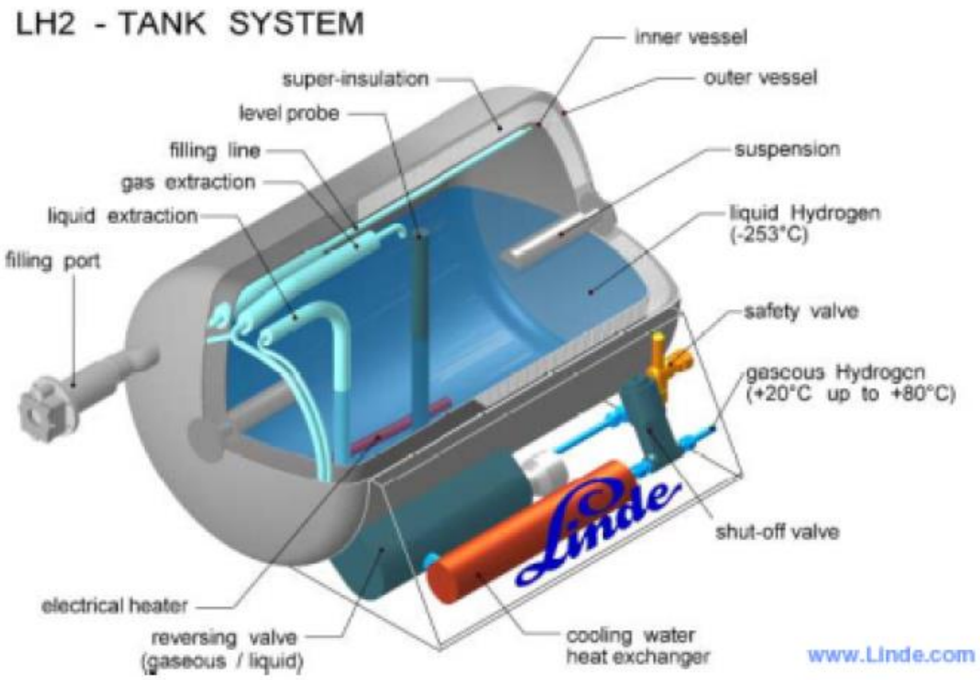


Figure 2.8 : Schematic representation of a cryogenic vessel – design and components[63]

Other issues associated with liquid hydrogen are the fuelling equipment and transferring lines, which have to be properly insulated to avoid losses. The weakest link in the whole process is the dismountable part known as “cryogenic coupling” in the connection region of the two cryogenic transfer lines. Linde AG claims that it has an improved design for this component with potential for further optimization. It promises an easy and safe handling operation, with minimized liquid hydrogen losses, high filling rate and short filling/refilling and coupling/decoupling times.

6.3 **Storage in métal hydrides**

Metal hydrides are based on metallic alloys and they act like a sponge absorbing gaseous hydrogen. Through a chemical reaction, solid metal hydrogen compounds are formed, under hydrogen pressure, and heat is released. Conversely hydrogen is released when heat is applied to the materials, through, for instance, heating of the tank and by reducing the pressure. The hydrogen molecule is first absorbed on the surface and then dissociated as strongly bound, individual hydrogen atoms. The metals are alloyed to optimize both the system weight and the temperature at which the hydrogen can be recovered. When the hydrogen needs to be used, it is released from the hydride under certain temperature and pressure conditions. This process can be repeated many times without loss of storage capacity [62].Storing hydrogen in solid materials is, in principle, an alternative, high volume and safe(the hydrogen release is exothermic and heat is needed to proceed) but also efficient storage method. The key element is the ease of hydrogen recovery that is reflected in the dissociation pressure of the material, a temperature dependent property. The mechanisms and the thermodynamics involved in hydride formation from gaseous hydrogen should be better understood though. Tackling kinetics and performance in hydrides has proven to be a rather challenging issue, particularly when these materials must demonstrate high hydrogen capacities and reversibility in the temperature range of270-360K and at pressures of 1 to 10 bar [54].[62].[64]

6.4 **Storage in porous Systems**

Porous systems compared to gaseous and liquid media offer the advantage of lower pressure hydrogen storage, increased safety, design flexibility and reasonable volumetric storage efficiency. However, the technology is not yet mature. Also, there are no imminent solutions for avoiding weight/cost penalties, and tackling thermal management issues associated with this option. The materials included in this category are[65]

- Carbon based materials, nanotubes, nanofibres, activated carbons, activated fibres,carbons from templates, powders, doped carbons and cubic boron nitride alloys.
- organics, polymers, zeolites, silicas (aerogels), porous silicon.

7 Conclusions

Hydrogen production from SMR is a mature and widely used technology. Production from coal gasification and electrolysis is also increasing; electrolysis in particular serves markets such as vehicles where hydrogen with few impurities is required. These are mature technologies and are expected to have an important role in the future. Yet there is uncertainty in the literature about the future costs of these technologies. This is amplified by commodity price uncertainties and by the potential impacts of environmental legislation and taxation. Biomass gasification is a potential low-carbon alternative to these more mature technologies. Although the economics of using biomass have been examined by several studies, none of these has examined biomass with CCS, despite it having the potential toproduce hydrogen while simultaneously removing large quantities of CO2 from the atmosphere. More generally, CCS is a key enabling technology for hydrogen production from carbonaceous fuels in a low-carbon energy system. Although unabated hydrogen production from fossil fuels continues to be the most economic approach at the moment, the imposition of a substantial CO2 emissions tax would tend to greatly favour plants with CCS or with non-carbonaceous feedstock's. Electrolysis is the most difficult of the mature technologies to forecast future costs. Both capital and feedstock costs are currently higher than for other technologies. However, there is much more potential for electrolysis costs to reduce through innovation than for the other technologies. There is also much more uncertainty about the future price of electricity; although it is expected to rise as renewable replace fossil fuel generation, there are already periods in some countries when the price reduces to zero as renewable supply exceeds demand. Numerous other technologies are being developed to produce hydrogen from water. These are as yet at an early stage of development and it is difficult to produce a realistic estimate of their liveliest costs at the moment. Performing economic appraisals and reducing costs will be key challenges for the development of these technologies in the future.

chapter3 Vehicle hydrogen

1 Introduction

Hydrogen is one of the most interesting solutions for propelling the motor vehicles even though, globally speaking, we are still far from using it massively. Many car manufacturers have presented their prototypes and models driven by hydrogen with the aim to emphasize that there is a potential in it. The greatest advantage of hydrogen is the fact that it does not pollute the environment. It does not emit carbon in any form, which also applies to carbon dioxide, nitrogen oxides or particulates.

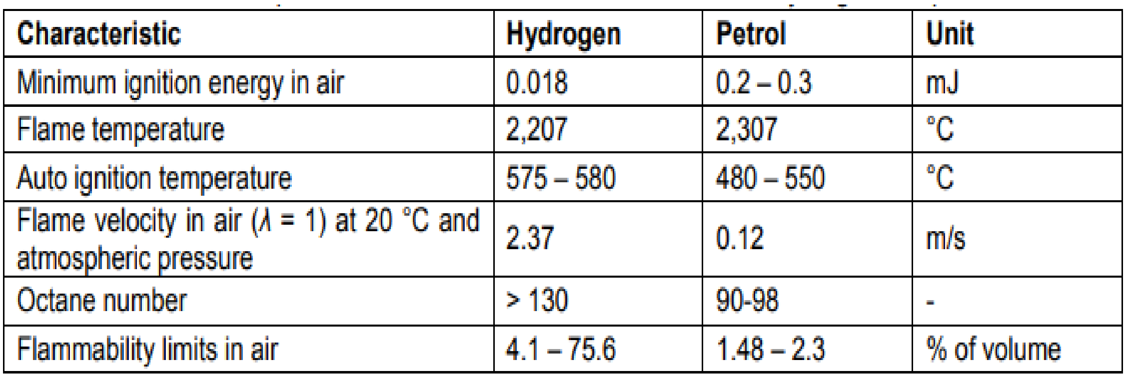
There are two types of hydrogen vehicles: vehicles using hydrogen as direct energy source and vehicles using fuel cells. The former use IC engines modified from standard petrol engines to burn hydrogen. However, the most popular hydrogen vehicles nowadays are the ones using fuels cells.

2 Propulsion using hydrogen combustion

Hydrogen can be used in conventional petrol engines as its flame spreads quickly from the ignition core throughout the chamber. However, due to smaller energy density of hydrogen compared to petrol, at pressures suitable for cylinder pistons, engine displacement must be two or even three times bigger than that of petrol engines (around 4 litters and 8 to 12 cylinders are needed), which is a problem in terms of space needed. The comparative overview of some characteristics of hydrogen and petrol is presented in Tab. 1 [66] [67].

Since large amounts of hydrogen are required to fill larger engine displacement, hydrogen needs to be much denser than it is possible in its gaseous form. Therefore, it is necessary to use liquid hydrogen cooled down to the temperature of around 20 K, as well as special filling stations. Such technologies are already being developed and special tanks for liquid hydrogen have already been designed (with multiple metal cylinders with appropriate insulation). However, it is also necessary to solve the problems of heat dissipation and hydrogen leakage

Table 3-1 Comparative overview of certain characteristics of hydrogen and petrol



Characteristic	Hydrogen	Petrol	Unit
Minimum ignition energy in air	0.018	0.2 – 0.3	mJ
Flame temperature	2,207	2,307	°C
Auto ignition temperature	575 – 580	480 – 550	°C
Flame velocity in air ($\lambda = 1$) at 20 °C and atmospheric pressure	2.37	0.12	m/s
Octane number	> 130	90-98	-
Flammability limits in air	4.1 – 75.6	1.48 – 2.3	% of volume

Hydrogen as a vehicle motor fuel is easier to use in public transportation vehicles. The engine and tank size problems are relatively easy to solve in city buses, because of more space is available, including the roof. Hydrogen propulsion using IC engine can be achieved by modifying existing engine in a certain way: valve thermal treatment, installation of non-platinum tip spark plugs, higher coil voltage, injectors designed for gas (not liquid) usage, more durable gasket materials, higher temperature engine oils etc. Many manufacturers have experimented with hydrogen engines. Mazda has developed Winkle engine for hydrogen combustion, an Austrian company named Alset has developed hybrid hydrogen/petrol system for Aston Martin Rapide S which participated in 24 Hours Nürburgring race [69], and BMW has developed their own supercar reaching the speed of 301 km/h burning hydrogen [68].

2.1**Direct injection hydrogène fuelled ICE (DI-H_2ICE)**

The power obtained in a compression ignition (CI) motor used with hydrogen injection is about twice that of the same motor operated in the premixed mode [70]. In a CI motor, the injector allows injecting high-pressure hydrogen directly into the cylinder [71]. The tricky point of this design is not the structure of the engine block, but the design of the injection nozzle which controls how the pressurized hydrogen is spread in the combustion chamber [72]. Fig. 3 shows a schematic illustration of a suitable injector.

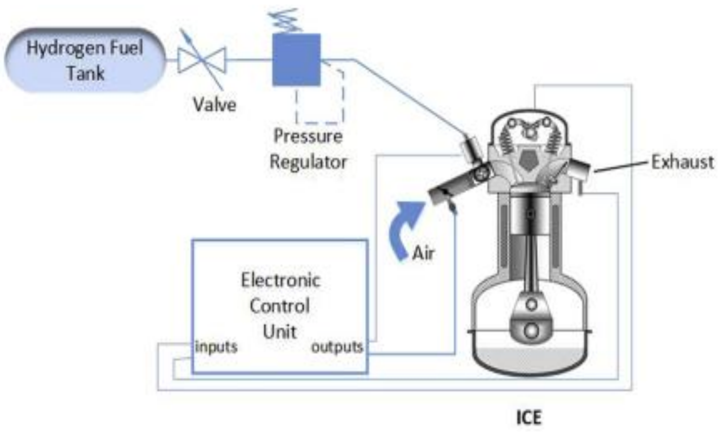


Figure 3-1 Schematic representation of pressure-boosted H_2ICE.

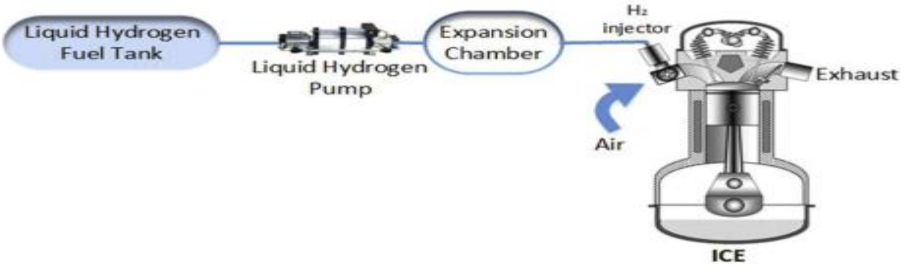


Figure 3-2 Schematic representation of liquid hydrogen storage and hydrogen injection system.

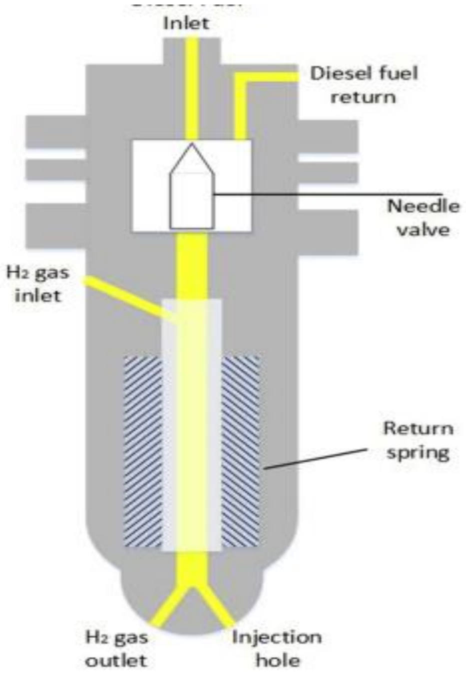


Figure 3-3 Schematic representation of injector used for DI-H_2ICE

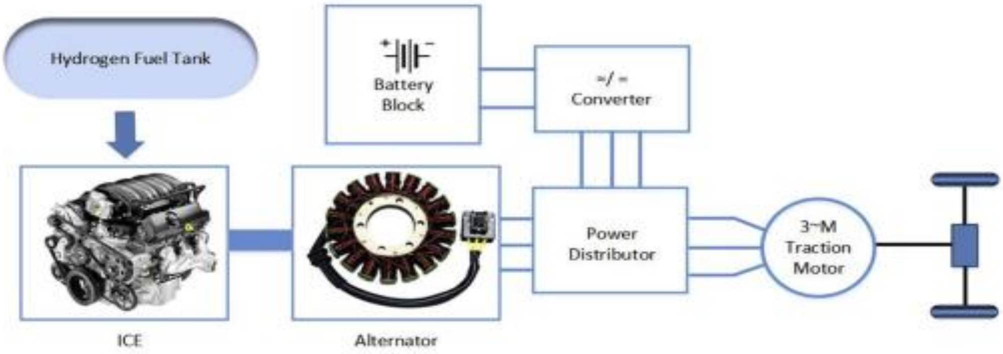


Figure 3-4 A hybrid-electric version of an H_2ICE

3 Propulsion using fuel cells

The increasingly popular technology widespread with hydrogen cars is the fuel cell technology. The fuel cell converts chemical energy into electric energy with the help of chemical reaction of positively-charged ions of hydrogen with oxygen or another oxidation agent. It is important to distinguish fuel cells from batteries because fuel cells need the flow of fuel and oxygen (air) in order to maintain the chemical reaction and produce electricity. This continuity in the production of electricity, as long as the fuel cell is supplied with fuel and oxygen (air), is its advantage.

Numerous studies have been carried out on energy and exergy analysis of various types of fuel cells [62e66]. These studies show that hydrogen and the fuel cell systems are highly efficient and that the fuel battery is one of the devices with the highest fuel efficiency among energy conversion systems [73][74]. In addition to the efficiency of a PEM fuel cell, the availability of transport by economic analysis at different loads has also been analysed [75][76].

Fuel cells are suitable with hydrogen owing to its abundance in nature [48], which is a renewable energy resource and ideal energy carrier in terms of sustainable product development, clean energy and safety. This means that hydrogen can be used to generate energy as a source of electrical energy in the hydrogen fuel cell vehicle [73]. The ability of fuel cells to convert hydrogen into free electrical energy without burning hydrogen with energy conversion efficiency is a great advantage. An ideal energy carrier, hydrogen, has more than twice of energy with energy content 120.0 MJ/kg as compared to liquefied natural gas, automotive gasoline, automotive diesel, with an energy content of 54.4 MJ/kg, 46.4 MJ/kg, 45.6 MJ/kg, respectively [77].

4 Hydrogen vehicles fuel cells

Hydrogen vehicles are a type of electric car that use fuel cells to power the motor instead of relying primarily on a lithium-ion battery pack; they don't burn fuel like gasoline cars. As with EVs, hydrogen cars don't generate harmful emissions—the only by-product is water vapour.

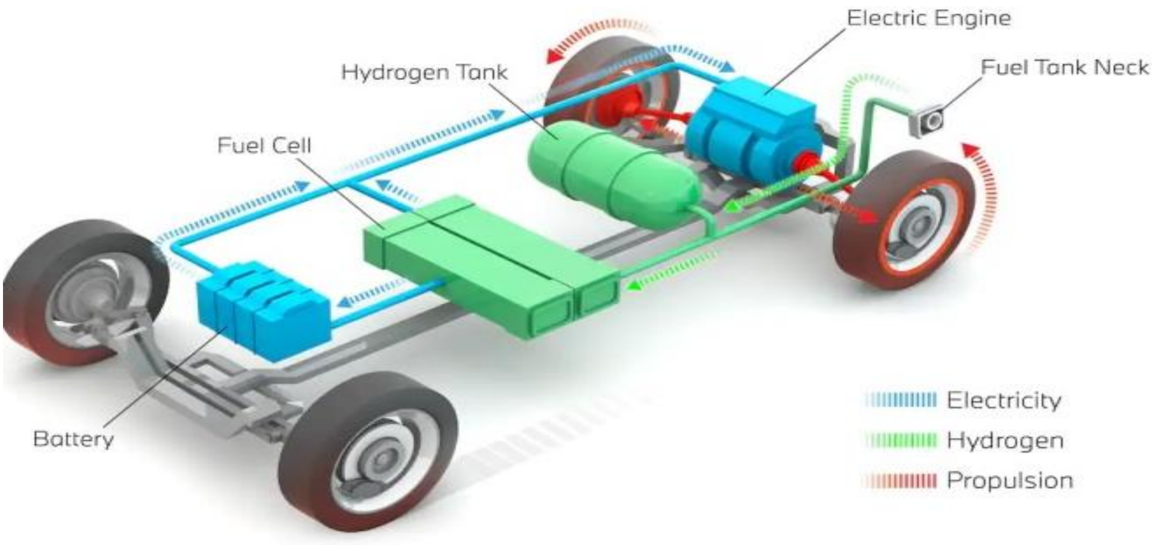


Figure 3-5 the hydrogen tank, battery, and electric motor all work together to power the FCEV

The fuel cells are similar in design to a lithium-ion battery: they have an anode, a cathode, and a catalyst that triggers the separation of electrons and protons from hydrogen gas pumped inside. Like the lithium-ion cells in an EV battery, hydrogen cars have multiple fuel cells working at once to generate electricity. That collection of cells is called the hydrogen fuel cell stack.

Hydrogen from the car's on board fuel tanks combines with oxygen inside the fuel cell stack to generate electricity via a process called reverse electrolysis. The electrons are removed from the hydrogen gas, sent through the circuit to power the motor, and combine with oxygen on the other side of the circuit to form water vapor, which is vented via the car's exhaust. [79]

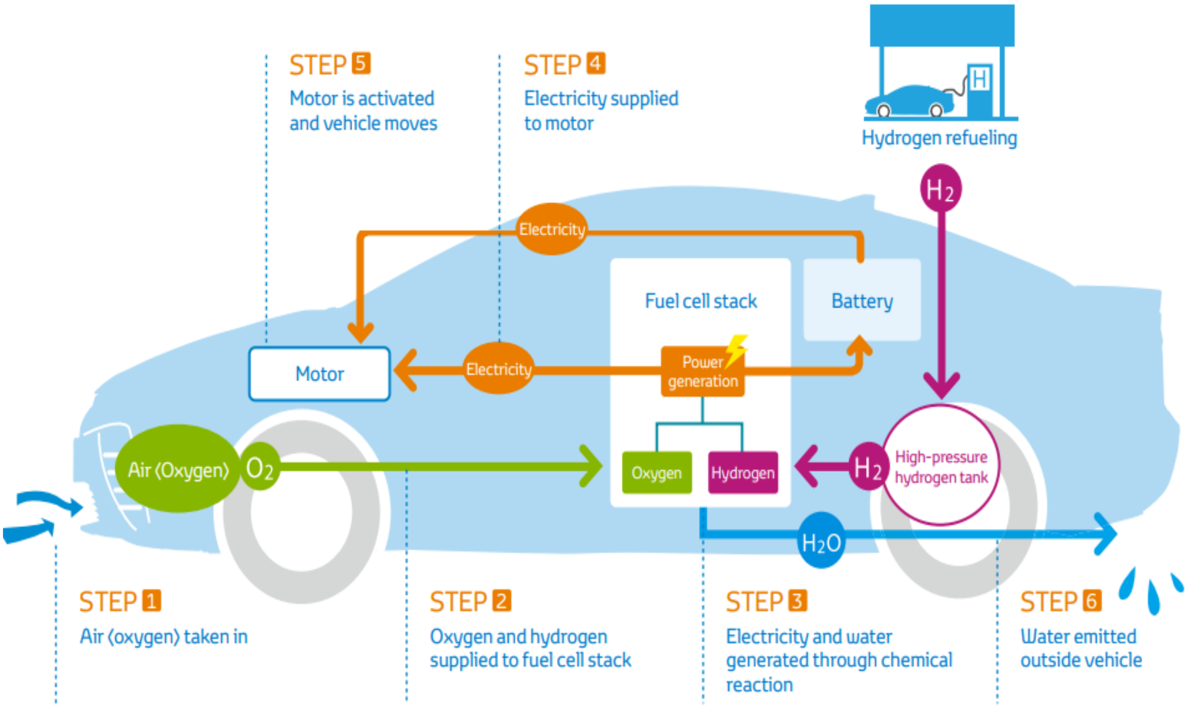


Figure 3-6 Operating principals

Essentially, there are no moving parts, it's just the chemical reaction that 'fuels' the action. It sees hydrogen enter the fuel cell from a tank and mix with oxygen to create H_2O in a chemical reaction, which generates electricity that is used to power the motors that drive the wheels.

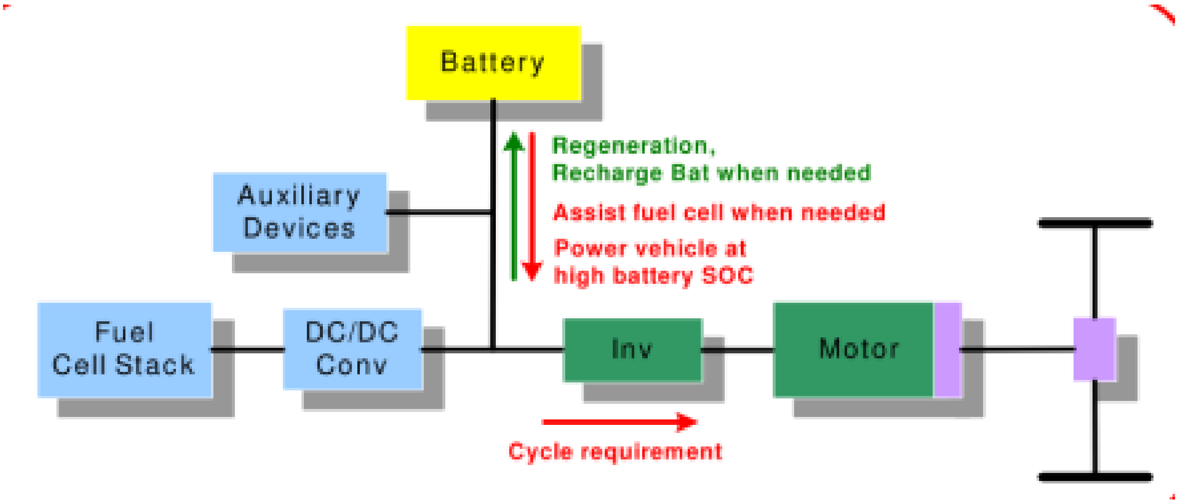


Figure 3-7 Basic structure of fuel cell based electric vehicle [73]

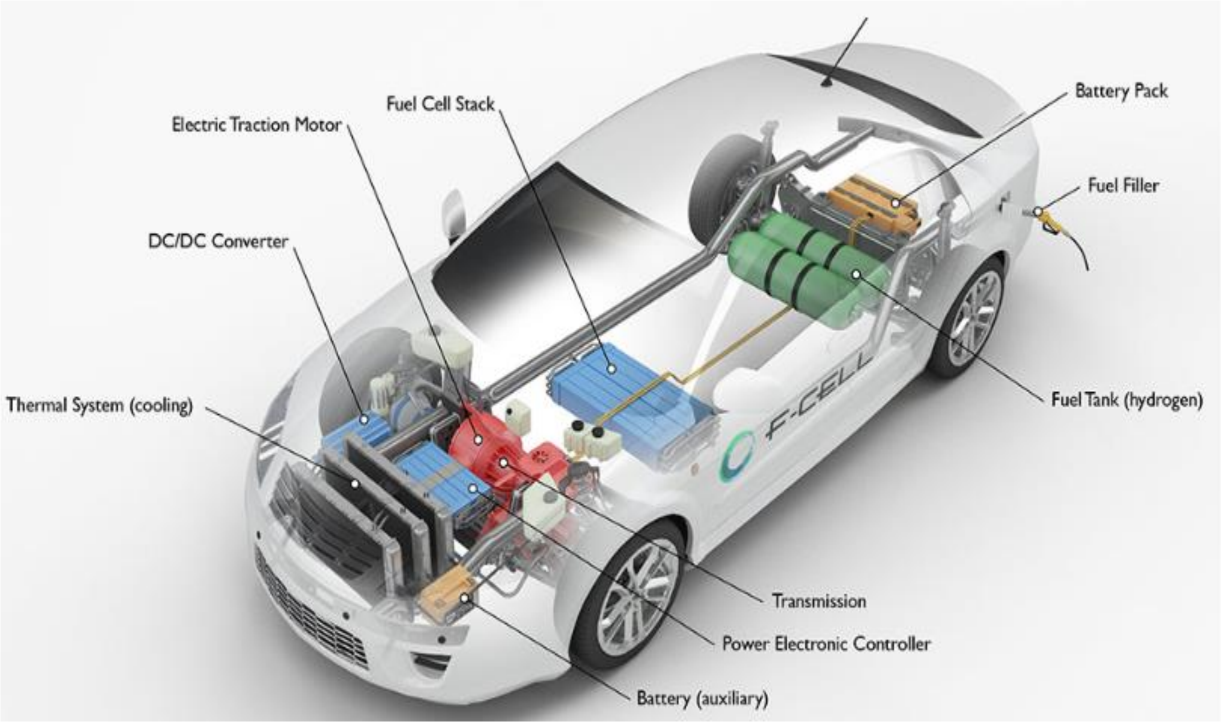


Figure 3-8 Schematic diagram of a hydrogen car

4.1**Fuel cell stack:**

An assembly of individual membrane electrodes that use hydrogen and oxygen to produce electricity

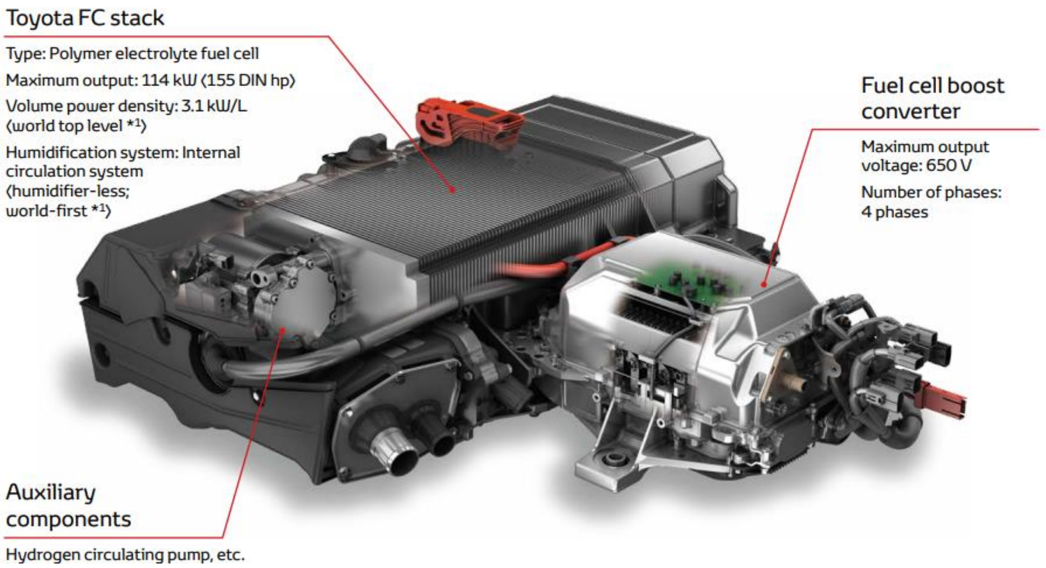


Figure 3-9Fuel cell stackToyota mirai make the fuel cells cheaply enoughز

The fuel cell is an electrochemical cell that converts chemical energy from a fuel into electricity. This electricity is generated from the reaction between hydrogen and an oxidizing agent, usually the oxygen in the air. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. This makes fuel cells very different to conventional batteries, because they consume the reactant, in this case hydrogen, from an external point, rather than carrying all the fuel within the device itself.

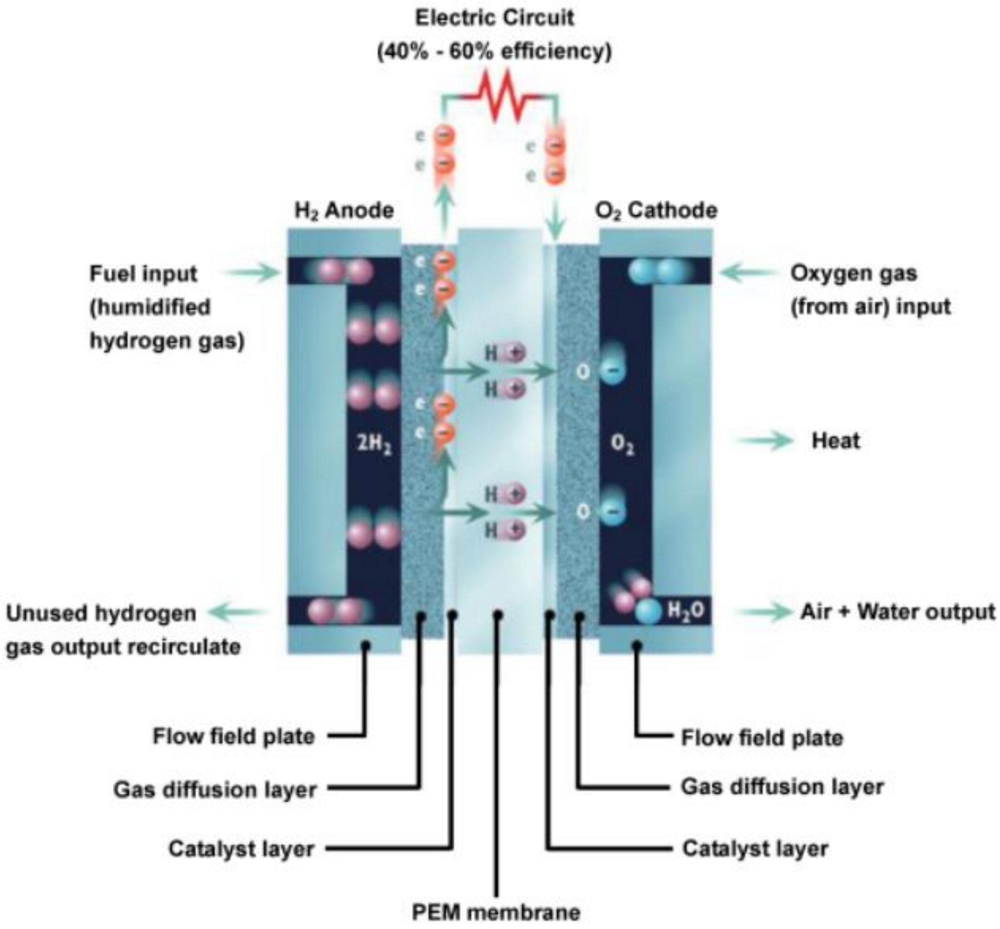


Figure 3-10 Fuel cell with polymer electrolyte membrane (PEM) - principle of operation

There are many types of fuel cells [77], but the principle of their operation is essentially the same (Fig3.11). Each of them has a cathode, an anode and an electrolyte which enable positively-charged hydrogen ions to flow inside the fuel cell. The cathode and anode have the catalyst which causes the fuel reaction so that it can generate positively charged ions and electrons. While hydrogen ions flow through the electrolyte after the reaction, electrons flow from the anode to the cathode through the external circuit, thus producing direct current. Fuel cells are mostly classified by the type of used electrolyte and by the time of the reaction initiation, which can vary from one second to several minutes. Besides electricity, fuel cells produce water and heat, as well as the small amount of nitrogen oxides and other emissions depending on the

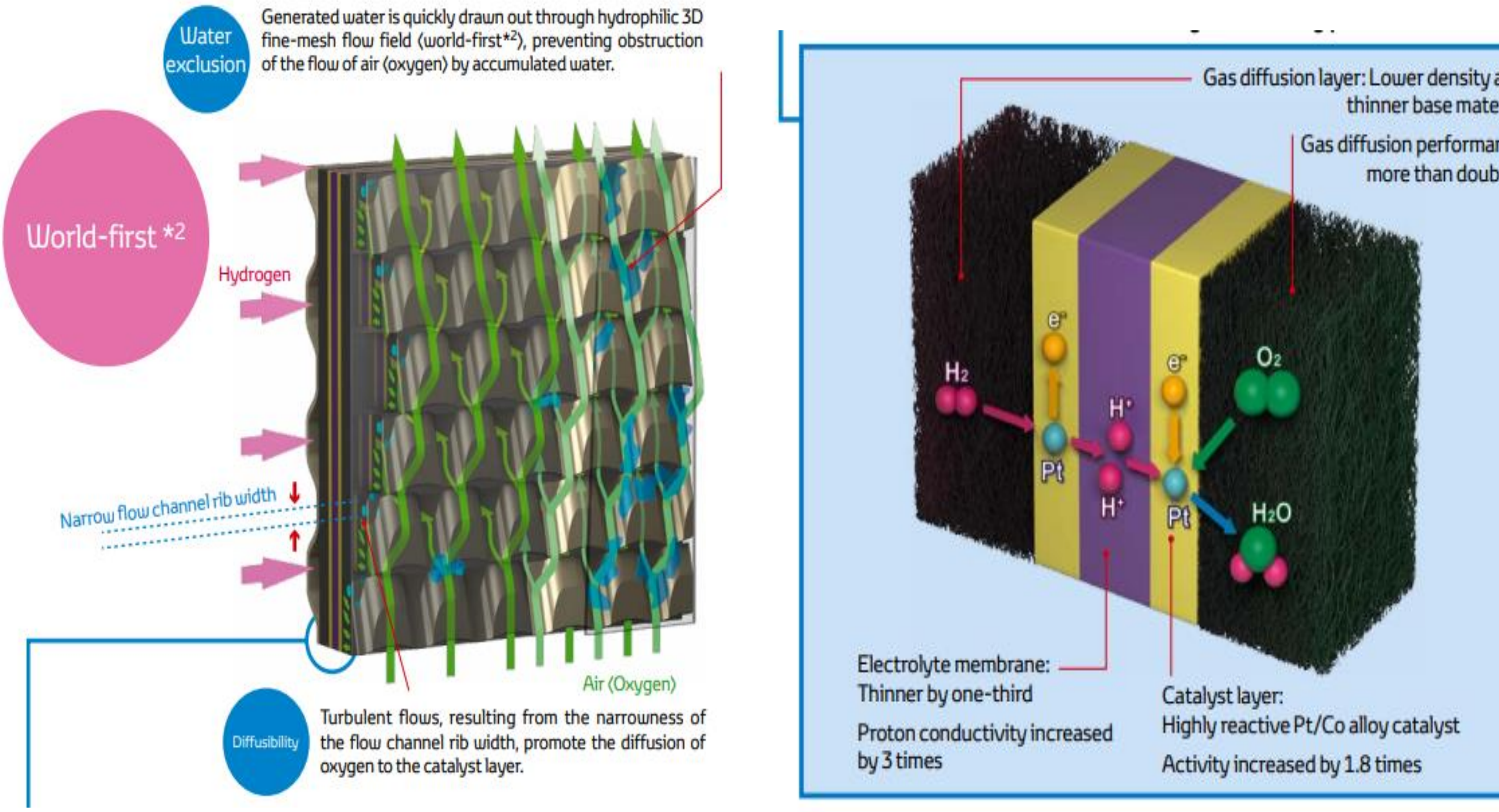


Figure 3-11 Innovations to cell flow channels (Cathode)

In a typical fuel cell; the anode (negative terminal) continuously is supplied with gaseous fuels, while the cathode (positive terminal) is fed with air containing oxygen .During the reaction, the hydrogen molecules are separated into proton and electron in the presence of a catalyst such as platinum [82][84]. The protons in the fuel cell pass through the electrolyte to the opposite side, while the electrons complete the charge through the load and reach the cathode [82][83][84]. Thus, electric current is generated between the electrodes by the electrochemical reaction [82][83]. The basic fuel cell working principle is illustrated in Fig. 5. If we want to know how the reactions occur between hydrogen and oxygen to produce an electric current, we can examine reactions occurring at each electrode [80].

Reaction in anode (oxidation)

$2H_2 \;=>\; 4H^+ + 4e^-$ ……………………………………………………………………………….18

Reaction in cathode (reduction)

$O_2 + 4H^+ + 4e^- \;=> 2H_2O$ …………………………………………………………………………….19

Net reaction (the redox)

$2H \quad + 2O \quad => 2H \quad O + electrisyty + heat$ ………………………………………………….20

In theory, fuel cells would function without losses, but that is not the case in real conditions. During their normal function, the major losses of the fuel cell are: activation losses which directly depend on the degree of the chemical reaction; voltage drop due to the resistance of the medium to the flow of ions and electrons; and concentration losses depending on the reactant concentration and their changes. Theoretical voltage which the fuel cell can achieve is somewhere around 1.2 V. However, due to the energy efficiency of the cell, which ranges from 40% to 60% [82], real operating voltage of the cell is between 0.45 and 0.72 V. Depending on the purpose of the fuel cells, they can be connected in two ways: in series (which produces higher voltage) or in parallel (which produces higher electric current). For the needs of motor vehicles, fuel cells are arranged in a way in which reacting gases must be uniformly distributed in all cells in order to gain maximum power output.

The type of electrolyte and its chemical composition determine the type of the fuel cell itself. The fuel it uses is also very important, but pure hydrogen is used most commonly. The anode catalyst, which is usually fine platinum powder, initiates the fuel and dissolves it into electrons and ions. Cathode catalyst, which is most often made of nickel, transforms ions into chemical compounds such as water or, rarely, dioxides of other elements. For the needs of hydrogen vehicle propulsion systems, fuel cells with polymer electrolyte membrane (PEM) represent an optimum choice

4.2 **Internal circulation system – Humidifier-less**

The new fuel cell stack performs self-humidification by circulating water produced from power generation within the cells, eliminating the need for external humidification. This makes it possible to eliminate the humidifier (world-first *1), making the system smaller and lighter

The system self-humidifies by circulating water (water vapour) produced from power generation within the cells in order to maintain the proton conductivity performance of the electrolyte membrane.

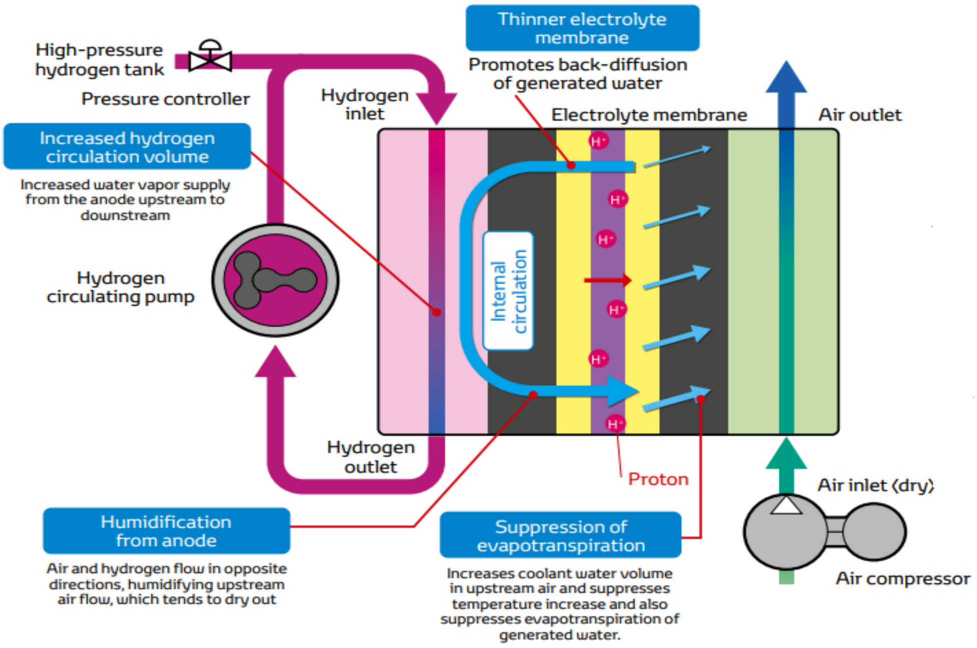


Figure 3-12 The system humidifies the supplied air (oxygen) using a humidifier to maintain the proton conductivity of the electrolyte

4.3 **Work motor Hydrogen Fuel Cell Electric:**

Among the distinguishing features of electric vehicles is the quiet, instantaneous, and smooth acceleration. That's because propulsion in an electric vehicle works differently. As their names suggest, the main difference between Hydrogen Fuel Cell electric vehicles and gasoline-powered cars is the fuel source. When you step on the accelerator of a Hydrogen Fuel Cell electric vehicle, electricity is sent from the battery to the electric motor, sending it rapidly spinning.

Battery (all-electric auxiliary): In an electric drive vehicle, the auxiliary battery provides electricity to power vehicle accessories

Power electronics controller: This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.

DC/DC converter: This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.

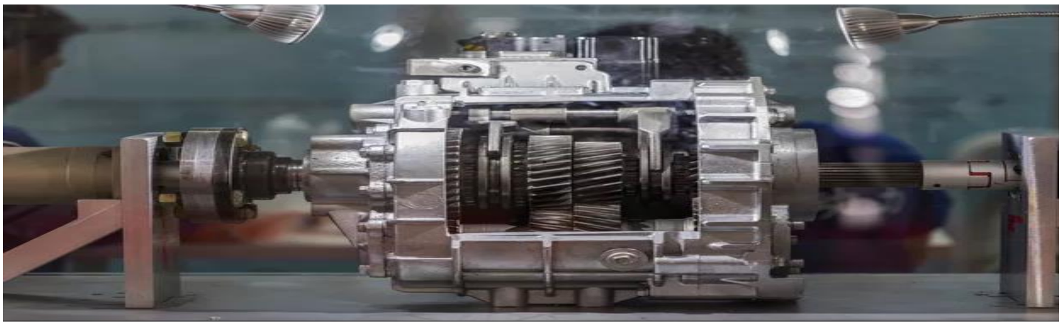


Figure 3-13 : Hydrogen Fuel Cell electric vehicle gearbox.

Most FCEV have a single AC (alternating current) motor connected to a gearbox. What is in the gearbox is what some people call a transmission since it is indeed a set of gears that transmits the rotation of the motor to the rotation of the wheels. But it is more accurately called a single-speed gear reduction unit since the multiple gears in the gearbox are always connected to each other and thus all spin at the same time.

The gear reduction unit reduces the RPMs of the motor to the more reasonable RPMs of the wheels at a ratio of roughly 10 to 1 course. So there is no clutch, no disengagement of gears, and no shifting between differently sized gears depending on the needs of the vehicle in other words, no transmission.

4.3.1 Reverse Gear:

Because the motor in a Hydrogen Fuel Cell electric vehicle usually uses alternating current, there is no need for a reverse gear. The motor merely spins in the opposite direction.

An AC motor can rotate anywhere from zero to 10,000 RPM or more. (The motor in a 2021 Tesla Model S Plaid can rotate up to 23,308 RPM, one of the reasons it can accelerate up to 200 miles per hour.) This givesFCEV plenty of torque at a wide range of speeds, with a “sweet spot” between enough torque and enough speed in the 30-40 mph range. Energy passes directly and nearly instantaneously from the motor through the gearbox to the wheels rather than through a transmission, and the transition from one speed to the next does not have to shift from one gear to the next, making for smooth and quiet acceleration.[87]

4.4Proposed onboard battery charge with duel functional circuit

Shows the conventional two-stage dual-voltage charging system which consists of an HV battery charger and an LV battery charger [88]. Also, the additional APD circuitis used to absorb the ripple power. In the two-stage charger, an AC/DC power factor correction (PFC) boost converter is usually combined with either non-isolated or isolated DC/DC converter. The main function of the second- stage DC/DC converter is to regulate the voltage and current of the HV battery. The advantages of the two-stage topology are that it provides high power factor, sinusoidal grid current, and ripple-less charging current [89].

A. Circuit configuration of proposed onboard battery charger

Figure 3.14 shows a circuit configuration of the proposed battery charger with dual functional. The first stage is a full bridge AC-DC converter, the second one is a dual active bridge (DAB) DC-DC converter, and the last one is a dual functional circuit (DFC) for LV battery charging and active power decoupling. For G2V or V2G modes, the SW1 is closed and the SW2 is connected to point “a”. In these modes, the HV battery is charged from the grid or releases power back to the grid, where the DFC works as an active power decoupling (APD) circuit which absorbs the inherent ripple power in the single-phase system. Next, for H2L mode, the SW1 is open and the SW2 is connected to point “b”. In this operation, the LV battery is charged by the DFC from the HV battery, where two identical capacitors (Cdc1 and Cdc2) are the output filter of the DAB converter.

B. Proposed lv battery charger with active power decoupling function

In order to achieve the APD function, the connection of the LV charger is moved to the DC link of the HV charger, rather than being connected directly to the HV battery. For an LV battery charger, the DAB converter and DFC are operated as a two-stage DC-DC converter. For an APD circuit, on the other hand, an auxiliary inductor, L r , is added. Then, the symmetrical half-bridge circuit with two identical capacitors, ==1 2 C CC dc dcf , and a small inductor, L r , is operated as an active power filter. The relay, SW2, is used for switching between APD function and LV battery charging. Furthermore, if the switching devices of the DFC are integrated with those of the single-phase full-bridge AC-DC converter, a three-phase intelligent power module (IPM) can be employed, which results in a compact design of hardware.

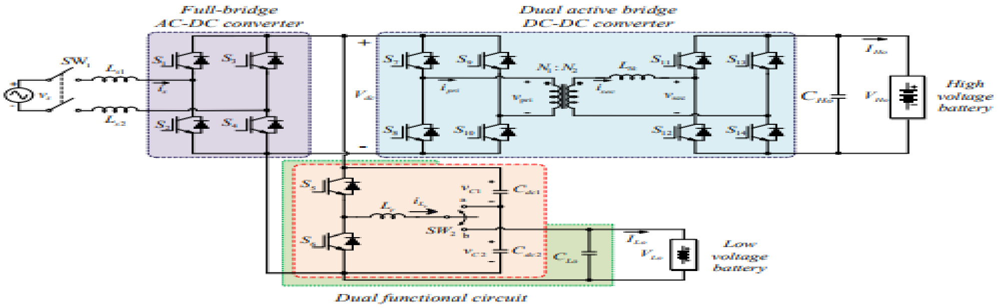


Figure 3-14 :Circuit configuration of the proposed onboard battery charger.

4.5 Before refuelling a hydrogen car:

Bring the vehicle to a complete stop with the hydrogen dispenser facing the nearside of the vehicle. Close all windows, shift the transmission selector to Park, and turn off the power.

Ensure the hydrogen dispenser is H70 rated, offering a supply pressure of 70MPa (700 bar). A full refuel will not be possible if the pressure inside the Mirai’s own hydrogen storage tanks is higher than the supply pressure from the hydrogen station.

Figure 3-15 Fuel filler Toyota mirai[1]

Release the lock for the fuel filler door by pressing the relevant dashboard button to the right of the steering column. Then open the fuel filler door by pressing the right-hand edge to release the push catch.

Remove the plastic dust cap covering the vehicle's hydrogen receptacle and store in the holder built into the fuel filler door.[90]

4.6. **Compressed hydrogen storage system**

The components of a typical compressed hydrogen storage system are shown in Figure3.17. The system includes the tank and all other components that form the 'primary pressure chamber' which prevents hydrogen from escaping from the system. In this case, the following components are part of the storage system compress

(a) The tank;

(b) The non-return valve;

(c) The shut-off valve;

(d) The thermo-controlled pressure-relief device (TPRD).

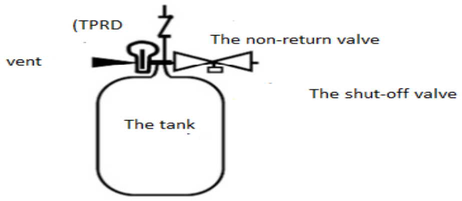
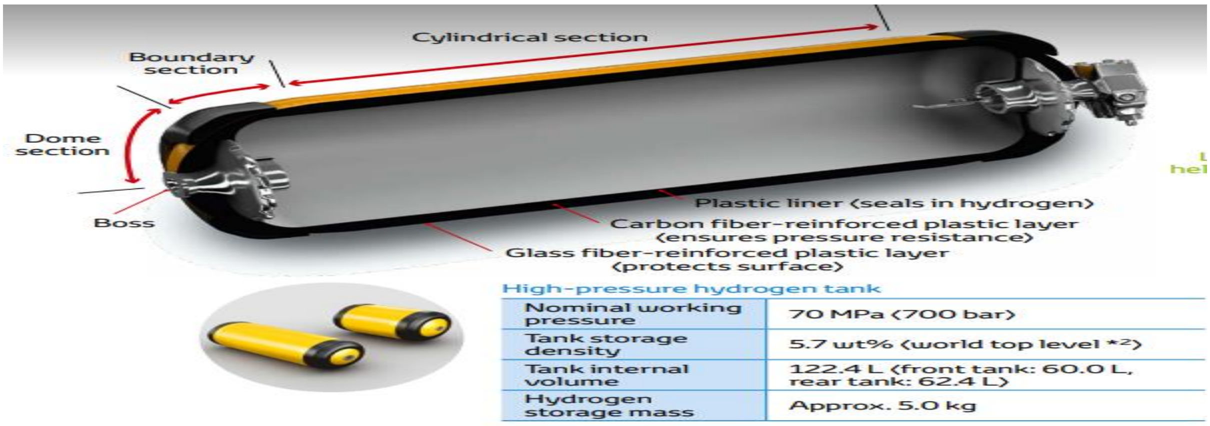


Figure 3-16 Typical compressed hydrogen storage system [90]



High-pressure hydrogen tank

Nominal working pressure	70 MPa (700 bar)
Tank storage density	5.7 wt% (world top level *2)
Tank internal volume	122.4 L (front tank: 60.0 L, rear tank: 62.4 L)
Hydrogen storage mass	Approx. 5.0 kg

Figure 3-17 Tank components [3]

Hydrogen storage tanks are used to store compressed gas. A hydrogen storage system may have more than one tank, depending on the quantity which must be stored and the physical constraints existing on the vehicle in question. Hydrogen fuel has a low energy density per unit volume. In order to overcoming this limitation, hydrogen is stored at very high pressure in the tanks storage of compressed hydrogen. On current research vehicles (i.e. prior to 2011), hydrogen is commonly stored at a nominal working pressure35 or 70 Map, with maximum filling pressures of 125% of the nominal service (either 43.8 or 87.5 Map respectively). During the normal operation of 'fast' filling, the internal pressure of the tanks can increase by 25 % above the nominal working pressure due to the fact that adiabatic gas compression causes a rise in temperature in the tanks. When cooling occurs in the tank after refueling, the pressure goes down. By definition, pressure after stabilization in the system is equal to the nominal working pressure when the tank is at 15 °C. Different pressure values (higher or lower, or intermediates between current values) may be applied in the future to teas the commercialization of techniques evolves.

The tanks are currently constructed of composite material in order to be able to meet the conditions for containment of high-pressure hydrogen with weight acceptable for application on the vehicle. Most storage tanks of high-pressure hydrogen used on fuel cell vehicles consist of two layers: an inner jacket that prevents leakage or gas permeation (usually made of metal or thermoplastic polymer) and an outer shell that ensures structural integrity (usually made of a metal or resin composite thermosetting reinforced with impregnated fiber wrapped around the jacket interior sealing).

During filling, hydrogen enters the storage system through anon-return valve. The non-return valve prevents the flow of hydrogen in the opposite direction in the filling pipe.

Automated hydrogen shut-off valve prevents hydrogen outflow stored when the vehicle is not in operation or when a defect is detected that makes it necessary to isolate the hydrogen storage system.

In the event of fire, thermo-controlled pressure-relief devices (TPRDs)allow a controlled release of the gas contained in the storage tanks compressed hydrogen, before the high temperatures resulting from the firedog not weaken the tanks and cause a dangerous rupture. [91]TPRDs are designed to quickly evacuate the entire contents of a tank. They do not allow resealing orre-pressing the tank. Storage tanks and TPRDs that have been exposed to a fire must be removed from service and destroyed

4.7**Hydrogène supply system**

The hydrogen supply system transfers hydrogen from the storage up to the propulsion system at the appropriate pressure and temperature forth supply of the fuel cell or internal combustion engine. To that end, this System includes a series of flow control valves, pressure regulators, filters, piping and heat exchangers. On storage-system vehicles of liquefied hydrogen, hydrogen, whether in liquid or gaseous form, can be extracted from the storage system and then heated to the appropriate temperature before being routed to the internal combustion engine or fuel cell system. In the in the case of vehicles with compressed hydrogen storage system, it may also be necessary to subject hydrogen gas to a heat conditioning treatment, especially at temperatures well below zero.

The fuel supply system must reduce the hydrogen pressure from the value in the hydrogen storage system to the appropriate value to power the fuel cell system or internal combustion engine. In the in the case of a hydrogen storage system compressed to 70 MPa of PSN, for example, it may be necessary to reduce the pressure by as high a value as 87.5 MPa toeless than 1 MPa at the inlet of the fuel cell system, or generally less than1.5 MPa at the entrance of an internal combustion engine system. This pressure reduction may require the use of multiple stages of regulators in order to achieve adjustment accurate and stable and to ensure effective protection of downstream equipment in the event of failure of a regulator. Overpressure protection of the power supply system can be achieved by the evacuation of hydrogen gas by means of decompression or cut-off of the hydrogen inlet (by closing the shut-off valve of the hydrogen storage system) when a case of downstream overpressure is detected.[91]

4.8**Electric Motors**

An electric motor is a mechanical device that converts electrical energy into motion, and that can be further adapted to do useful work such as pulling, pushing, lifting, stirring, or oscillating. It is an ideal application of the fundamental properties of magnetism and electricity. Before looking at DC motors and their properties, let’s review some fundamentals.

Magnetism and electricity

are opposite sides of the same coin. Electrical and electronics design engineers regularly utilize Maxwell’s four laws of electromagnetism based on Faraday’s and Ampere’s earlier discoveries in their daily work. They might tell you, “magnetism and electricity are inextricably intertwined in nature.” In fact, you don’t have one without the other. But usually you only look at one or the other unless you are discussing electric motors or other devices that involve both.

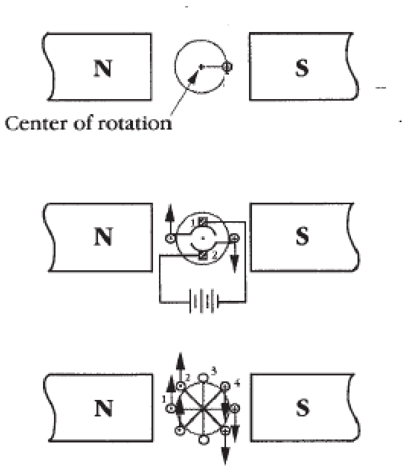


Figure 3-18 DC motor s basics—obtaining torque from moving conductor s.

4.8.1 DC Motors in the Real World

Now it's time you met real-world DC motors—their construction, definitions, and efficiency. Let's start by looking at their components

- **Armature**

The armature is the main current-carrying part of a motor that normally rotates (brushless motors tend to blur this distinction) and produces torque via the action of current flow in its coils. It also holds the coils in place, and provides a low reluctance path to the flux. (Reluctance is defined as (H 3 1)/4 and measured in ampere-turns per lines of flux.) The armature usually consists of a shaft surrounded by laminated sheet steel pieces called the *armature core*. The laminations reduce eddy current losses; steel is replaced by more efficient metals in newer designs. There are grooves or slots parallel to the shaft around the outside of the core; the sides of the coils are placed into these slots. The coils (each with many turns of wire) are placed so that one side is under the north pole and the other is under the south pole; adjacent coils are placed in adjacent slots,. The end of one coil is connected to the beginning of the next coil so that the total force then becomes the sum of the forces generated on each coil

- **.Commutator**

The commutator is the smart part of the motor that permits constant rotation by reversing the direction of current in the windings each time they reach the minimum flux point. This piece is basically a switch. It commutates the voltage from one polarity to the opposite. Since the motor rotor is spinning and has momentum, the switching process repeats itself in a pre-ordained manner. The alternating magnetic poles continue to provide the push to overcome losses (friction, wind age, and heating) to reach a terminal speed. Under load, the motor behaves a bit differently, but the load causes more current to be drawn. Physically, it's a part of the armature (typically located near one end of the shaft)that appears as a ring split into segments surrounding the shaft. These segments are insulated from one another and the shaft.

- **Field Poles**

In the real world, electromagnets (recall your toolbox nail with a few turns of insulated copper wire wrapped around it) are customarily used instead of the permanent magnets you saw in Figure 6-1 and Figure 6-2. (Permanent magnet motors are, in fact, used, and you'll be formally introduced to them and their advantages later in this section.) In areal motor the lines of flux are produced by an electromagnet created by winding turns of wire around its poles or pole pieces. A pole is normally built up of laminated sheet steel pieces, which reduce eddy current losses; as with armatures, steel has been replaced by more efficient metals in the newer models. The pole pieces are usually curved where they surround the armature to produce a more uniform magnetic field. The turns of copper wire around the poles are called the field windings

- **Series Motors**

How these windings are made and connected determines the motor type. A coil of a few turns of heavy wire connected in series with the armature is called a *series motor*. A coil of many turns of fine wire connected in parallel with the armature is called a *shunt motor*.

- **Brushes**

Typically consisting of rectangular-shaped pieces of graphite or carbon, brushes are held in place by springs whose tension can be adjusted. The brush holder is an insulated material that electrically isolates the brush itself from the motor frame. A small flexible copper wire embedded in the brush (called a *pigtail*) provides current to the brush. Smaller brushes can be connected together internally to support greater current flows.

- **Motor Case, Frame, or Yoke**

Whatever you wish to call it, the function of this part is not only to provide support for the mechanical elements, but also to provide a magnetic path for the lines of flux to complete their circuit—just like the lines of flux around a bar magnet. In the motor's case, the magnetic path goes from the North Pole through the air gap, the magnetic material of the armature, and the second air gap, to the south pole and back to the north pole again via the case, frame, or yoke. Motors operating in the real world are subject to losses from three sources:

• **Mechanical**—All torque available inside the motor is not available outside because torque is consumed in overcoming friction of the bearings, moving air inside the motor (known as wind age), and because of brush drag

.•**Electrical**—Power is consumed as current flows through the combined resistance of the armature, field windings, and brushes.

• **Magnetic**—Additional losses are caused by eddy current and hysteresis losses in the armature and the field pole cores. In summary:• Efficiency is simply the power out of a device, relative to the power applied to the device.• When you apply 100 watts, and get only the work equivalent to 90 watts out of it, you have a 10-watt loss. That is a 90 percent efficient device.• That rule of efficiency applies to motors, motor speed controllers, battery chargers, etc.

4.8.2 DC Motor Types

Now that you've been introduced to DC motors in theory and in the real world, it's time to compare the different motor types. DC motors appear in the following forms:

- Series
- Shunt
- Compound
- Permanent magnet

- Brushless
- Universel

4.8.3 Permanent Magnet DC Motors

When you were first introduced to the DC motor topic, permanent magnets were used as an example because of their simplicity. Permanent magnet motors are, in fact, being increasingly used today because new technology—various alloys of Alnico magnet material, ferrite-ceramic magnets, rare-earth element magnets, etc.—enables them to be made smaller and lighter in weight than equivalent wound field coil motors of the same horsepower rating. Rare-earth element magnets surpass the strength of Alnico magnets significantly (by 10–20 times), and have been used with great success in other areas such as computer disc drives, thereby helping drive down the production costs. (SeeFigure3.19) While commutator and brushes are still required, you save the complexity and expense of fabricating a field winding, and gain in efficiency because no current is needed for the field.

Brushless DC Motors [94]

With no brushes to replace or commentator parts to maintain, brushless motors promise to be the most long-lived and maintenance-free of all motors. You can now custom tailor the motor's characteristics with electronics (because electronics now represent electronics

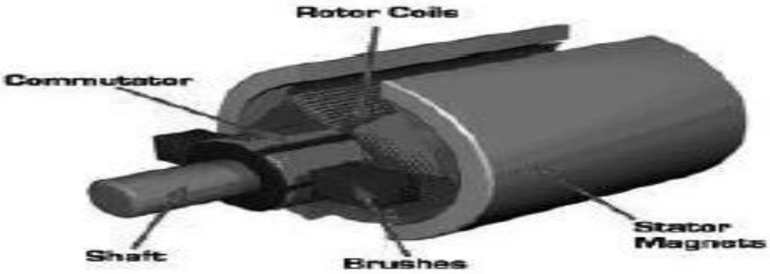


Figure 3-19 Permanent magnet DC motor [93]

and the distinction between DC motor types blurs. the brushless motor more closely resembles an AC motor (which you'll meet in the next section) in construction. Assume that brushless DC motors resemble their permanent magnet DC motor cousins in characteristics—shunt motor plus high starting torque plus linear speed/torque—with the added kicker of even higher efficiency duet no commentator or brushes. There are other manufacturers of DC motors.

4.8.4 Universal DC Motors

Although any DC motor can be operated on AC, not all DC motor types run as well on AC and some might not start at all (but will run once started). If you want to run a DC motor on AC, you have to design for it. A series DC motor type is usually chosen as the starting point for universal motors that are to be run on either DC or AC. DC motors designed to run on AC typically have improved lamination field and armature cores to minimize hysteresis and current losses (see Figure 3.20) Additional compensating orient pole windings can be added to the armature to further reduce commutation problems by reducing the flux at commutator segment transitions. In general, series DC motors operating on AC perform almost the same (high starting torque, etc.), but are less efficient at any given voltage point. [94].

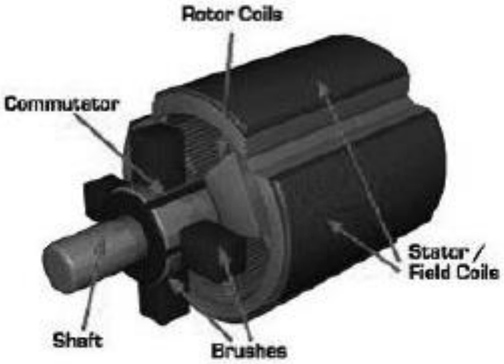


Figure 3-20 DC motor with round stator

The application of a motor in a vehicle doesn't need to contend with multiple sources of power. Universal motors are typically used in appliances, and not much at that, given what happened to the world during the oil crises in 1973 and 1979. Efficiency became a watchword, and a NASA patent was eventually put into the public domain. This resulted in the "Green Plug," which is now standard equipment in all new motor driven appliances. These motors shouldn't be put in EVs of any sort. There are bette solutions. [93]

4.9**Cooling system motor**

With the development of advanced materials and innovative manufacturing technology, high thermal conductivity materials and advanced structures for electric motor cooling have been studied. Hasset et al. [95] proposed a motor cooling system using heat pipes. The heat pipe evaporator was inserted into the motor housing to absorb heat, while the condenser was placed in a cooling chamber for heat rejection. Shoai-Naini et al. [96] [97] developed a heat pipe based thermal bus for motor cooling with system performance studied for various driving cycles. Putra et al. [98] proposed a motor cooling system with L-shaped heat pipes. In addition, new motor internal structures that benefit the system cooling have been studied. Lee et al. [99] presented a permanent magnet motor design with a hollow shaft which allows coolant flow to help promote cooling.

A variety of electric motor thermal management methods are summarized in Fig. 21 including air, liquid, heat pipes, and hybrid cooling. Air cooling is straightforward and offers a simple structure but the cooling performance may not be sufficient. Moreover, a cooling fan is usually linked to the motor shaft which consumes energy and cannot be directly controlled. Liquid cooling is effective; however, it consumes energy to run the coolant pump and radiator fan. On the other hand, liquid cooling adds more weight and complexity due to the cooling lines. Heat pipes can operate passively in the presence of a temperature gradient; however, they have heat transfer limitations due to the capillary limit, fluid properties, operating temperatures, etc. This research proposes a hybrid cooling system (refer to Fig21d) which features two parallel heat transfer pathways – heat pipes and liquid. By adding heat pipes, the workload of the liquid heat transfer pathway may be reduced, providing possibilities to minimize the cooling system energy consumption.

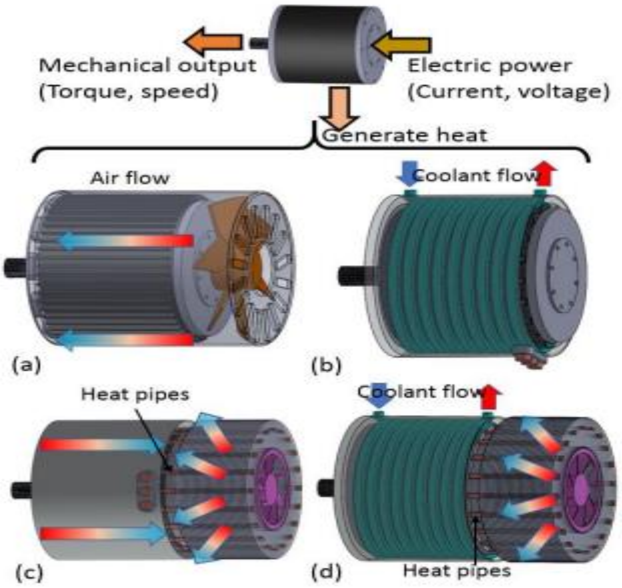


Figure 3-21. Overview of select electric motor cooling strategies – (a) Surface air cooling with a fan coupled to the shaft, (b) Liquid cooling with coolant jacket, (c) Heat pipe cooling with attached fins and a centrifugal fan, and (d) Hybrid cooling with heat pipes and liquid.

Cooling system featuring two heat transfer pathways, heat pipes and liquid, will be designed for a military HEV's electric motors. The compact system consists of an electric motor, a circular-shaped thermal cradle with external helical coolant jacket, heat pipes inserted into the cradle, and finned structure heat exchanger to reject heat to the surroundings while the motor and fins are protected by a shell

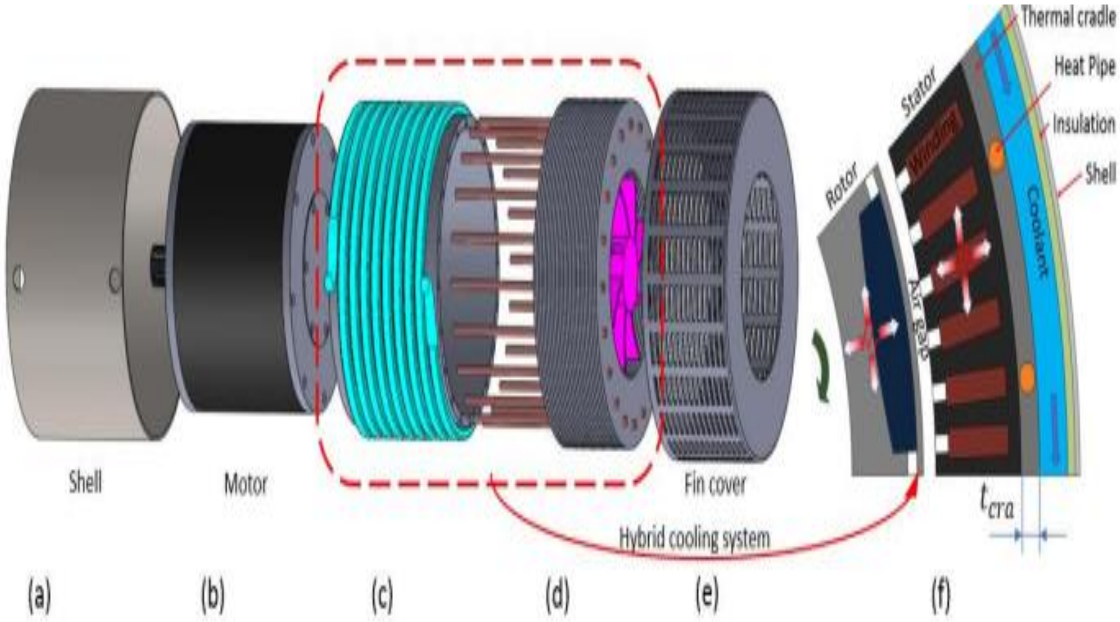


Figure 3-22 Electric motor cooling system configuration – (a) motor shell; (b) electric motor; (c) thermal cradle and coolant jacket; (d) heat pipes, fin structure heat exchanger, and centrifugal fan; (e) heat exchanger cover; and (f) cutaway view of motor cooling concept

And cover (refer to Figs. 22a – 22e). The electric motor generates the thermal load while the cradle, coolant jacket, and heat exchanger assembly are the heat regulating elements. The cradle design offers a hybrid cooling solution by integrating a helical coolant jacket for the liquid and a cluster of slots for the heat pipes. One end of the heat pipes is embedded in the axial slot while the other end has an array of circular fins to increase the heat transfer area. A centrifugal fan placed inside the heat pipe structure induces forced convection when needed. A sectional view of the motor and cradle assembly is shown in Fig. 22f. [100]

Heat pipes were selected for this thermal management system due to their relatively very high effective thermal conductivity while remaining completely passive. A heat pipe has two sections: an evaporator (hot end) and a condenser (cold end). The working principle is displayed in Fig. 3.23 . It can be observed that the heat transfer process starts with heat supplied to the evaporator end. The heat pipe wick is made of a porous material filled with a working liquid. This liquid is vaporized as a result of the input heat. The vapor is then pushed towards the condenser through the vapor chamber, and condenses back to liquid by rejecting heat. Finally, the liquid from the condenser end returns to the evaporator through the wick based on capillary forces. Fins and a fan are added to enhance the heat dissipation rate (see below).

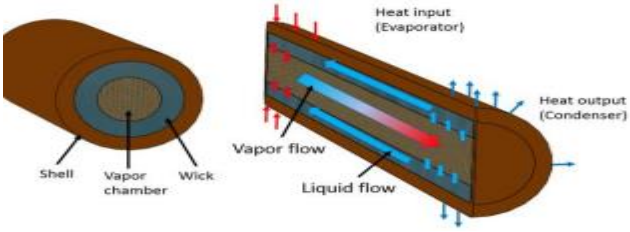


Figure 3-23 Working principle and temperature distribution of a heat pipe

A hybrid truck's power train may be composed of an engine generator set and four electric motors located at the wheels (refer to Fig.3.30). The traditional engine cooling system contains a pump, radiator with fan(s), and thermostat valve to regulate engine block temperature. The addition of electric motor in the wheel assemblies provides an opportunity for inserting the hybrid thermal management system. The motor may be cooled either by heat pipes alone or by heat pipes (passive) and liquid (active) simultaneously depending on the required heat load. The motors' liquid heat transfer pathway would be completed by adding a water pump, a radiator, and hoses to connect the four motors. To ensure consistent cooling for each motor, the coolant exiting from the radiator is evenly divided into four streams to each wheel, and the streams will merge before returning to the radiator. As a result, the motor at each wheel may be cooled simultaneously by regulating the water pump and radiator fan speeds. The actuators (centrifugal fans, radiator fan, and coolant pump) enable the motor's operating temperature to be regulated by adjusting the air and coolant flow rates. Furthermore, the hybrid cooling system provides opportunities to reduce the workload of the liquid cooling pathway by adding heat pipes. [100]

Figure 3-24 electric vehicle chassis schematic with liquid and heat pipe motor cooling.

4.10 Power electronic architecture and fuel cell vehicle

The hybrid FCEV is a type of electric vehicle in which both the fuel cell and the battery provide electrical power to drive the train of the vehicle. In FCEV, oxygen from the air is combined with the stored hydrogen to generate power for driving the electric motor. From a fuel tank, hydrocarbon gas is transferred to the fuel reformer to achieve purity of hydrogen gas and is stored in the fuel cell stack. As per the requirement of power, hydrogen for fuel cell stacks is combined with oxygen from the air to generate electricity, and excess electricity can be saved in batteries or ultra-capacitors. There are different types of fuel cells available in the market, such as polymer electronic membrane (PEM), direct methanol fuel cells, phosphoric acid fuel cells, regenerative fuel cells, reformed methanol fuel cells, solid oxide fuel cells, and molten carbonate fuel cells. Both hybrid and fuel cell vehicles are pollutant-free, and the by-product is water. The schematic block diagram of hybrid and fuel cell vehicle is shown in Fig. 3(a). The operating mode of FCEV is divided to five modes, as shown in Fig. 3(b). In fuel mode, the fuel cell acts as a source of energy to propel the train individually. In battery mode, the battery works as a source of energy to drive the train. If both the battery and fuel supply are together, then it is called a "combined mode. In split mode, the fuel cell supplies power to drive the vehicle, and excess energy is utilized to charge the battery. Ina regenerative mode, the traction motor acts as a source to charge the battery [100]

FCEV, the electric energy is generated from the battery and fuel cell. The main goal of FCEVs is to convert electrical energy from fuel cells to usable power for various loads of the vehicle by using an efficient method to improve the efficiency and performance of the vehicle. Low voltage DC equipment’s, such as mobile charger, auto starters receives power directly from a battery or fuel cell. For motor drive and high voltage applications, the low voltage is stepped-up to 300 V us-ing a step-up DC-DC converter. The traction controller is adapted to maintain the required speed of the vehicle by varying the amplitude and frequency of the inverter output. The voltage controller is adapted to maintain the maximum and minimum charging levels of the battery and to increase its life, as shown in Fig. 3.25. In FCEV electrical system, bidirectional DC-DC power converter plays a key role to controlling the energy flow from the fuel cell to a traction motor during motor mode and from the motor to the battery during regenerative braking mode in hybrid FCEV. The bidirectional DC-DC power converter controls the energy flow with the help of traction and voltage controllers

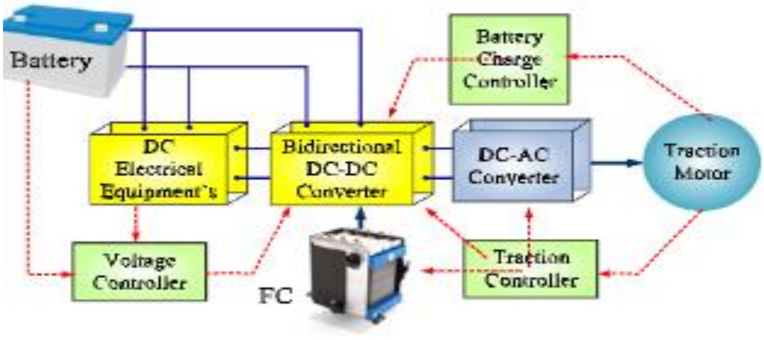


Figure 3-25 Control scheme of FCEV.

5 Conclusion

In this paper, an investigation into hydrogen-based energy generation using fuel cells and their utilization in hybrid vehicles was conducted. Various types of FCs and their applications were analyzed, namely the application of FCs in hybrid vehicles. FCs with adequate control strategies could become the more advantageous choice for applications in vehicles over batteries alone. Hydrogen fuel cells will play a significant role in the transportation industry in the near future. The price of fuel cells will reduce when producing fuel cells in large quantities and commercializing them. We could expect fuel cell-based transportation, power plants, and electricity generators to become prominent in the coming decades

chapter4 Safety analysis in hydrogen process

1 Introduction

All fuels are dangerous because they are highly chemical reactive. It is this reactivity that makes fuels excellent sources of energy. Hydrogen is not inherently more dangerous than other fuels, such as natural gas or gasoline, but its properties are unique and must be handled with appropriate care. In many ways, hydrogen is safer than other fuels.

Hydrogen leaks form the basis of all gaseous hydrogen hazards, since without a leak there is no opportunity for hydrogen to mix with air, and therefore no basis for flammability or asphyxiation hazards. In addition to leaks, the low temperature of liquid hydrogen forms the basis for frostbite and oxygen condensation hazards.

2 Hydrogen Leaks

The properties of hydrogen that contribute to its leak hazard are:

- it has the lowest molecular weight, and the smallest molecule, of any element
- it has the lowest density and therefore highest buoyancy of any element
- it can cause embrittlement in some materials
- it is colourless, odourless and tasteless
- it acts as a simple asphyxiate when present in a sufficient concentration to reduce the level of oxygen

The small size of hydrogen molecules makes them more difficult to contain than the molecules of other gases. To a large extent, the potential for hydrogen leakage is minimized through design. Materials of construction are designed for hydrogen use and are resistant to metal embrittlement. Fuel lines never pass through the passenger compartment, eliminating the potential for hydrogen to leak into the vehicle

- However, since hydrogen is colorless, odorless and tasteless, its presence cannot be detected by humans, and there are no warning symptoms before unconscious-ness results.

Leakage gases may be hot and pose a burn hazard Leakage gas may pose a high-pressure hazard

- **Hydrogen Fires**

The properties of hydrogen that contribute to its flammability hazard are:

- it has the widest flammability range of any fuel
- it has the lowest ignition energy of any fuel
- it has the greatest energy per weight of any fuel
- it burns invisibly and without smoke
- it can potentially generate electrostatic charges that result in sparks through flow or agitation

Once leaked, hydrogen mixes with air and is flammable over a wide range of concentrations. This flammable mixture is very easy to ignite, and, once ignited, burns with great vigour. The flame is nearly invisible in daylight. If hydrogen leaks into an enclosed environment, the risk of combustion and explosion is increased. If hydrogen leaks into an open environment, it rises quickly and is rapidly diffused, reducing the risk of fire. Existing fires burn vertically and generally for short periods of time.

- Most mixtures of hydrogen and air are potentially flammable and explosive, and can be easily ignited by a spark or hot surface. Hydrogen flames are almost invisible in daylight**.**

To some extent, the potential for fire is reduced through design. Materials of construction are fire-resistant and are thoroughly grounded to prevent static charge accumulation. High-pressure fuel storage cylinders include pressure relief devices that are designed to release the cylinder contents when immersed in fire, thus preventing explosive pressure build-up within the cylinders. The pressure relief device discharge is routed to vents that protrude to the top surface of the bus canopy, allowing unimpeded access to the atmosphere.

- The fueling and venting facility must be grounded together with the vehicle to prevent static electrical discharge. Suitable facility fire detection, fire extinguishing equipment and procedures must be in place

- **Extinguishing a Hydrogen Fire**

The protocol for fighting a hydrogen fire is similar to fighting any fire fuelled by a gas. The main thing to do is eliminate the fuel source. If this is not an option, allow the fuel to burn itself out under controlled conditions. The object is to minimize the risks of injury and danger to people, and risk of damage to equipment in the surrounding area. As with any fire, evacuate all personnel except those fighting the fire, contact local fire authorities if needed, and fight the fire from as great a distance as possible.

3 Low Temperature Hazard

The property of hydrogen that causes a low temperature hazard is:

- it has second lowest boiling point of all substances, after helium.

Low temperature hazards only exist when hydrogen is stored in liquid form. The extremely low temperature of liquid hydrogen results in severe frostbite danger and secondary fire danger.

Liquid hydrogen is stored below –423 ºF (–253 ºC; 20 K) in vacuum-lined vessels. Liquid hydrogen vessels must be completely insulated with specified materials to prevent any contact with the vessel.

- A severe frostbite hazard danger occurs whenever skin comes into contact with liquid hydrogen, liquid hydro-gen vapors or surfaces directly in contact with liquid hydrogen. Any skin contact can cause extensive tissue damage, burns, freezing or tearing.
- Any surface in contact with liquid hydrogen poses a severe frostbite danger.

3.1 High Température:

Water, glycol solutions, oils and gases circulate through pipes and other vessels within a transit bus. The maximum temperature achieved by any of these streams is the turbocharger compressor outlet, which can exceed 400 ºF (200 ºC). Exposed surfaces can cause serious burns if touched.

During normal operation, engine compartment covers pre-vent exposure to hot surfaces; however, the engine may be operated with the engine covers open. If the covers are open, such as during maintenance procedures, contact with any internal surfaces containing circulating liquids or gases must be avoided. Internal components may remain hot for a long time after the engine has been shut down.

- Avoid contact with internal surfaces that are in contact with liquids or gases. Heed all warning decals.

4 High Pressure:

Hydrogen to fuel a transit bus is typically stored in roof-mounted cylinders at an operating pressure of up to 3600 psig (250 barg), and potentially as high as 5000 psig (345 barg). Personnel handle hydrogen at high-pressure when fueling these cylinders. This high-pressure is extremely dangerous and could result in an explosive force if a leak or component rupture occurred. Even when depleted, the hydrogen cylinders are often at a residual pressure of 300–500 psig (21–35 barg).

- Never crack open or loosen the fitting of any high-pressure component; doing so may cause the fitting or component to be propelled with extreme force. Never tighten a high-pressure fitting while under pressure; doing so could cause the fitting to shatter with serious personal injury. Follow fueling and venting procedures exactly.

The hydrogen cylinders and high-pressure circuit are pressurized even when the engine is shut down.

5 Electrical Shocks

A fuel cell powered transit bus contains a variety of high and low voltage components.

Fuel cell stacks produce voltage in proportion to the number of fuel cells, and overall levels can exceed 1000 VDC (open circuit voltage) for a heavy-duty engine such as for a transit bus. This is converted to AC power within an inverter to operate the drive motor. The inverter adjusts the AC output frequency and current to achieve a prescribed torque set-point and the output voltage floats as required, but can reach levels as high as 460 VAC.

At times, some of this AC power is diverted into one or more water- or coolant-cooled bleed resistors (or “dump choppers”) where it is converted to heat. These high voltage components pose a severe shock or electrocution danger and can remain charged for up to five minutes even after the engine has shut down.

- Fuel cell engines contain high DC and AC voltages. Exercise caution when accessing electrical components to prevent shock or electrocution.
- Do not operate a fuel cell engine unless all high voltage barriers are in place
- Always assume that the fuel cell stacks are electrically charged. Do not touch the fuel cell stack, its graphite cells, or the cell voltage monitoring wires until you con-firm that no voltage exists.

5 Physical

Physical hazards include rotating equipment and weight hazards.

- **Rotating Equipment**

The fuel cell engine contains fans and belt-driven rotating equipment that may be partially exposed, or could become exposed if protective guards are removed.

During normal operation, engine and radiator compartment covers prevent exposure to these rotating components; how-ever, the engine may be operated with these covers open. If the covers are open, such as during maintenance procedures, contact with rotating equipment is possible and must be avoided.

Loose clothing may become entrained in rotating equipment and should not be worn

6 Fault tree Analysis

The objectif in this project is to analyse risks in hydrogen process and especial in car hydrogen engine.

In this section, we are interested in proton-exchange fuel cell (PEMFC), we have all set reliability targets for PEMFCs in automotive application of a lifetime of more than 5000 hours of operation (equivalent to around 240000km operation). The current state of fuel cell development struggles to meet these targets, and as such, an in-depth reliability analysis of PEMFCs is invaluable to help manufacturers and developers. Such an analysis requires obtaining a detailed understanding of the failure modes of all the different parts of the cell, and the effects the failures have on the cell as a whole.

Currently, the understanding of the reliability of PEMFCs is still in its infancy, and requires further development.

The work presented here uses the techniques of FTA to comprehensively ascertain key failure phenomena and analyse their role and effects within an automotive PEMFC system. Boundaries are set to only consider the PEMFC itself, the balance of plant and supporting ancillaries are omitted as shown in Figure4- 1, where the functional block diagram of a simple fuel cell automotive system is shown. The dotted rectangle shows the boundaries of the system considered here.

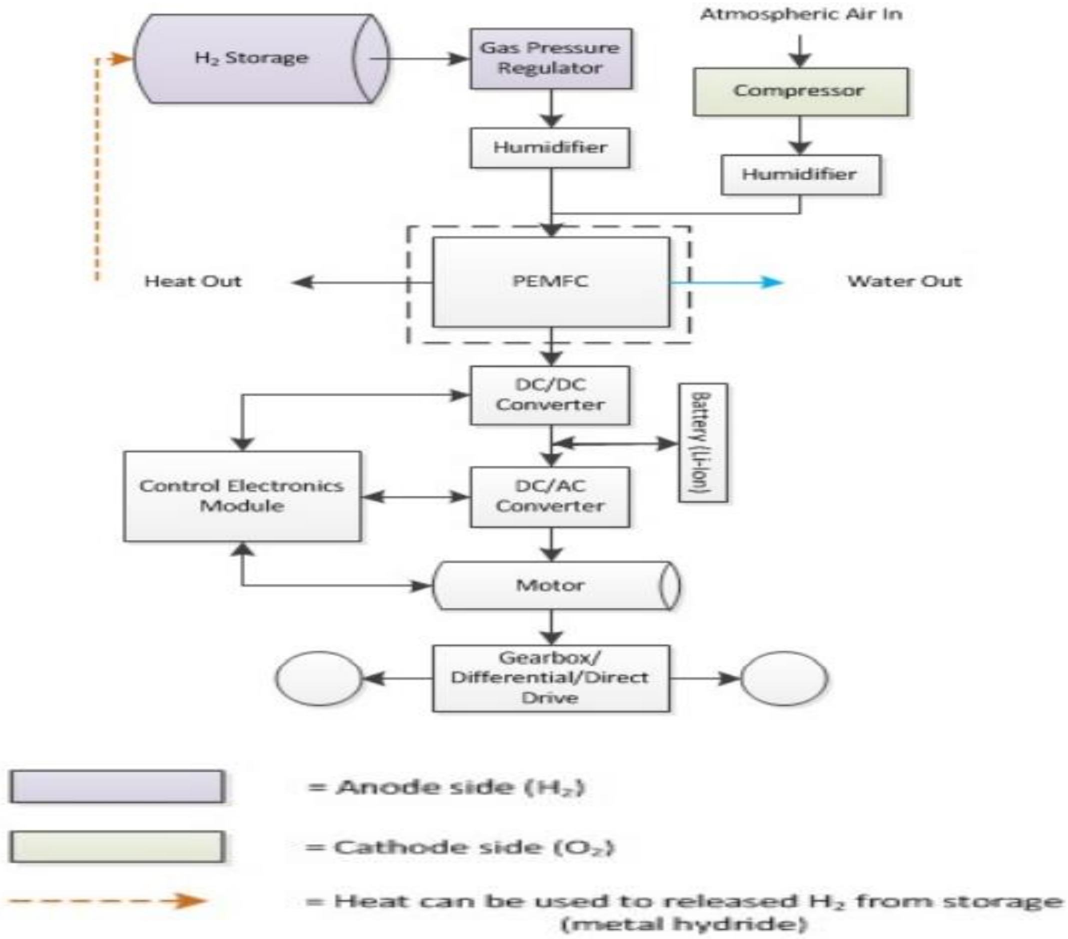


Figure 4-1 Boundaries of presented reliability analysis

The qualitative failure identification table presented, has proved to be a good start in identifying the multitude of failure modes in a PEMFC system.

7 Isograph Reliability Workbench 14.0

To create our Fault tree, isograph software is used.

Fully integrated reliability and safety software for the professional.

- Reliability block diagram analysis
- Fault tree, common cause and importance analysis
- Event tree analysis with multiple risk categories
- Markov analysis including multi-phase modelling
- Link hazard logs and requirements to RBD or fault tree verification models
- Multiple standards support for system analysis including ARP 4761, IEC 61508, ISO 26262
- Predict the reliability of electronic and mechanical components using MIL-217, Quaternion 217 Plus, SN29500, IEC 61709, FIDES, Telcordia TR/SR, IEC TR 62380, GJB299C and NSWC
- FMEA and FMECA to standards such as MIL-STD-1629A, BS 5760 Part 5, GJB 1391-92, AIAG & VDA, SAE J1739, ARP5580

Is developed by (company) in (year) for (objectives)

Following investigation into the operation of the PEMFC to understand the effect of the component failure modes described above, a FT was constructed to consider the event '5% drop of output voltage'. 15 basic events were found relating to this top event, and for which data is available for a quantitative analysis.

the interactions between basic event failure logic were vastly modified. The level 2 intermediate events are also presented in Figure4-2 Catalyst Layer Degradation, Membrane Degradation, Gas Diffusion Layer Degradation and Bipolar Plate Degradation. All intermediate events lead to a 5% drop in voltage corresponding with the top event.

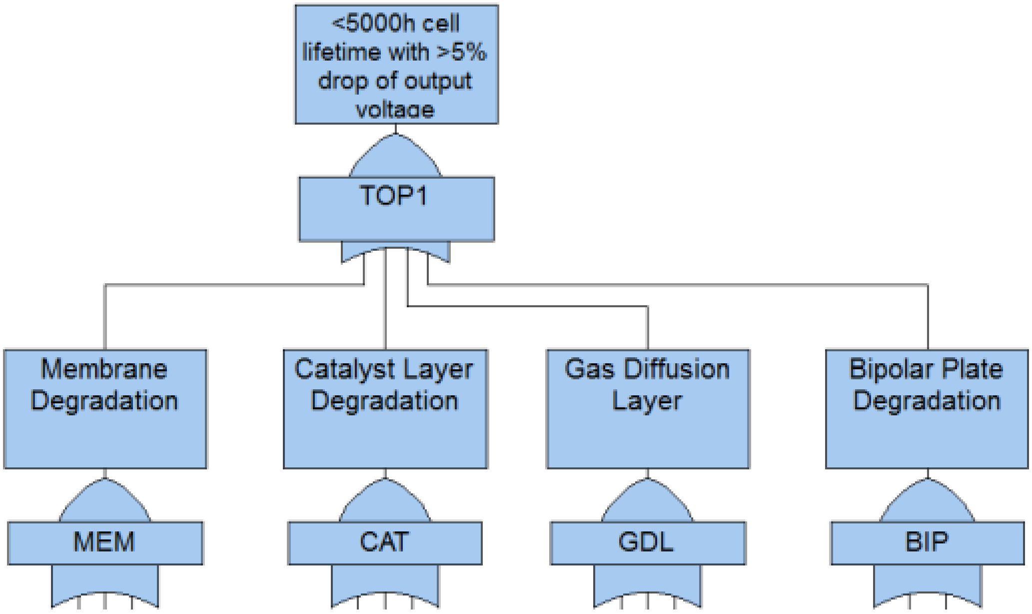
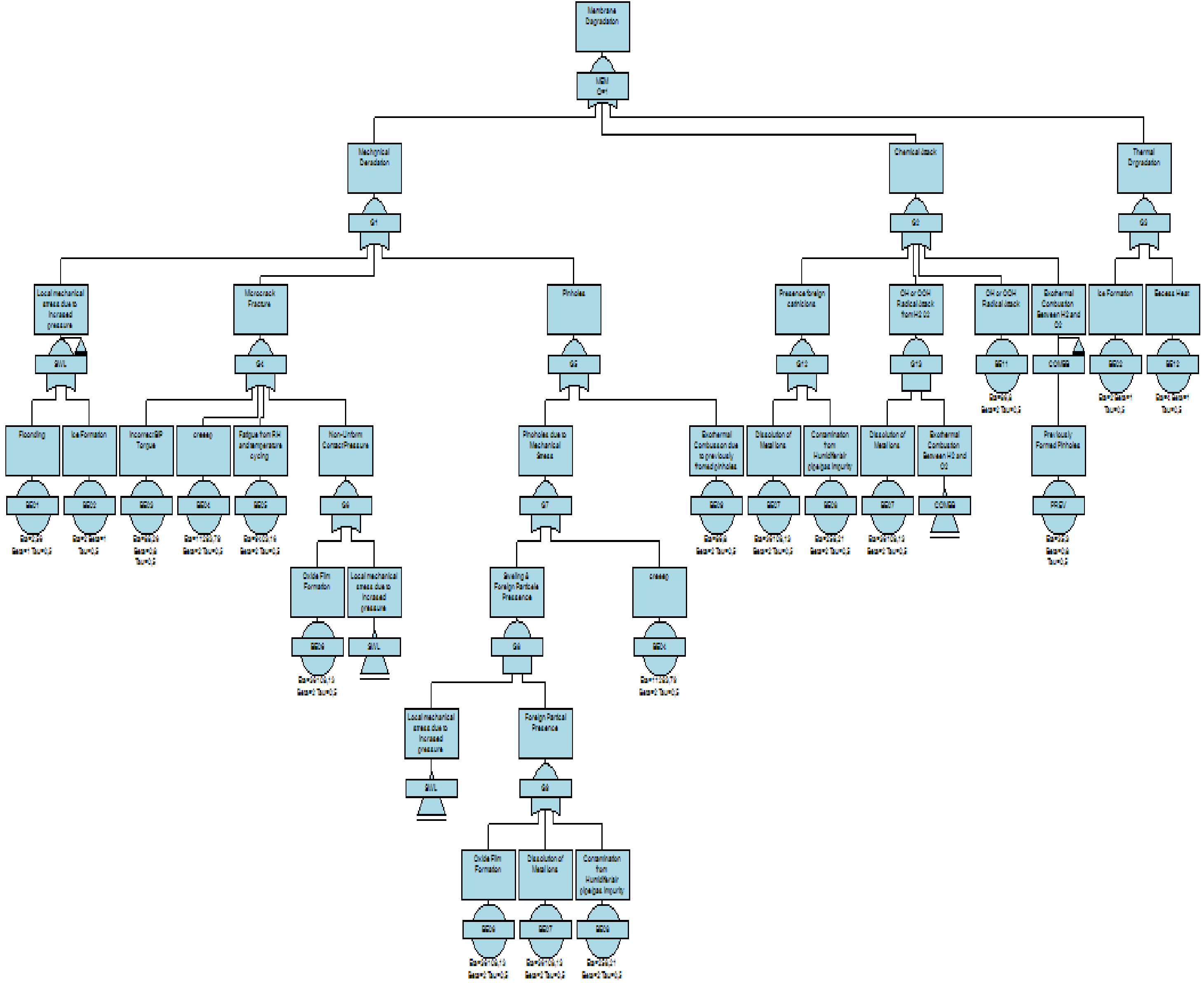
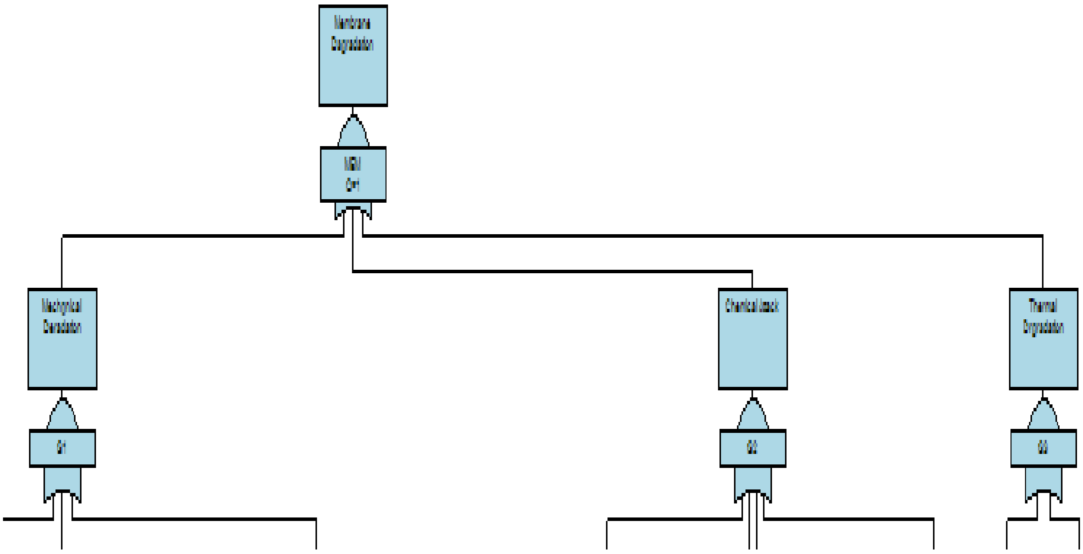
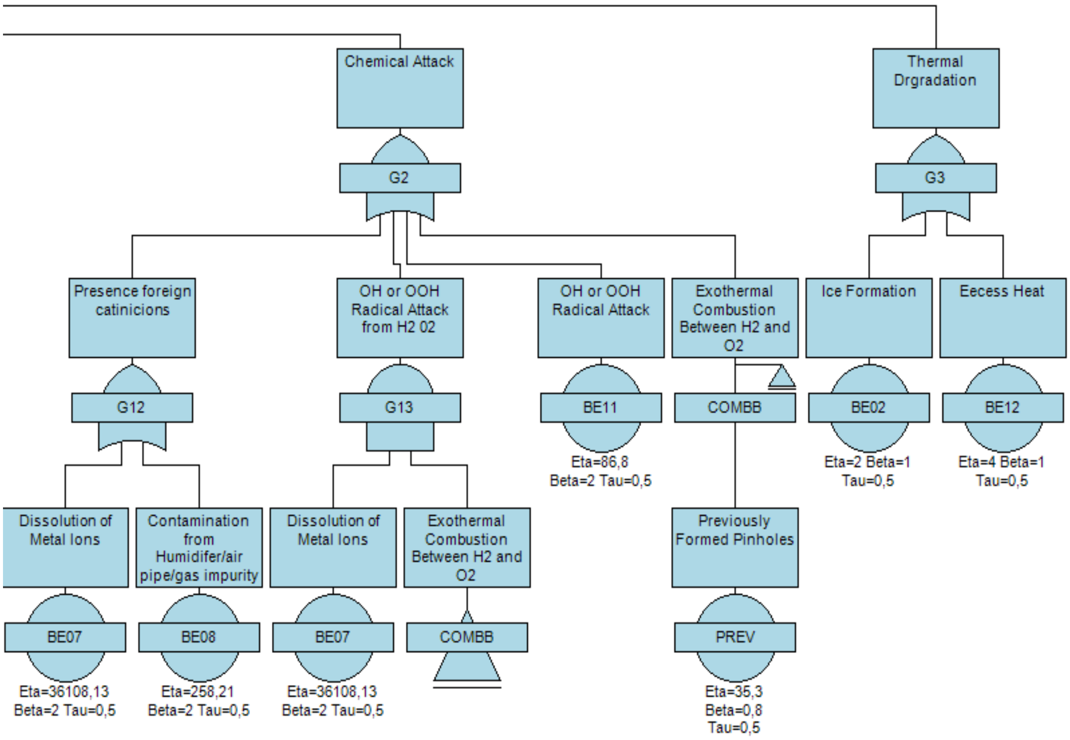


Figure 4-2 Proposed Change to 'Global' Tree

The membrane degradation branch of the global FT is further split down into the three main pathways of degradation in the membrane; 'Mechanical Degradation', 'Chemical Degradation' and 'Thermal Degradation', with the mechanical section being presented in figure4-3 for brevity.


Membrane Degradation
MEM Or
Mechanical Deradation
G1
Chemical attack
G2
Thermal Degradation
G3
Local mechanical stress due to increased pressure
SWL
Microcrack Fracture
G4
Pinholes
G5
Presence foreign cation ions
G12
OH or OOH Radical attack from H2 O2
G13
OH or OOH Radical attack
BE11
Exothermal Combustion Between H2 and O2
COMB
Ice Formation
BE02
Excess Heat
BE12
Flooding
BE01
Ice Formation
BE02
Incorrect BP Torque
BE03
creep
BE04
Fatigue from RH and temperature cycling
BE05
Non-Uniform Contact Pressure
G6
Pinholes due to Mechanical Stress
G7
Exothermal Combustion due to previously formed pinholes
BE09
Dissolution of Metal Ions
BE07
Contamination from Humidifier air pipe/gas impurity
BE08
Dissolution of Metal Ions
BE07
Exothermal Combustion Between H2 and O2
COMB
Previously Formed Pinholes
PREV
Oxide Film Formation
BE06
Local mechanical stress due to increased pressure
SWL
Swelling & Foreign Particle Presence
G8
creep
BE04
Local mechanical stress due to increased pressure
SWL
Foreign Partical Presence
G9
Oxide Film Formation
BE06
Dissolution of Metal Ions
BE07
Contamination from Humidifier air pipe/gas impurity
BE08


Membrane Degradation
Mechanical Degradation
G1
Chemical Attack
G2
Thermal Degradation
G3


Chemical Attack
G2
Thermal Drgradation
G3
Presence foreign catinicions
G12
OH or OOH Radical Attack from H2 02
G13
OH or OOH Radical Attack
BE11
Eta=86,8 Beta=2 Tau=0,5
Exothermal Combustion Between H2 and O2
COMBB
Ice Formation
BE02
Eta=2 Beta=1 Tau=0,5
Eecess Heat
BE12
Eta=4 Beta=1 Tau=0,5
Dissolution of Metal Ions
BE07
Eta=36108,13 Beta=2 Tau=0,5
Contamination from Humidifer/air pipe/gas impurity
BE08
Eta=258,21 Beta=2 Tau=0,5
Dissolution of Metal Ions
BE07
Eta=36108,13 Beta=2 Tau=0,5
Exothermal Combustion Between H2 and O2
COMBB
Previously Formed Pinholes
PREV
Eta=35,3 Beta=0,8 Tau=0,5

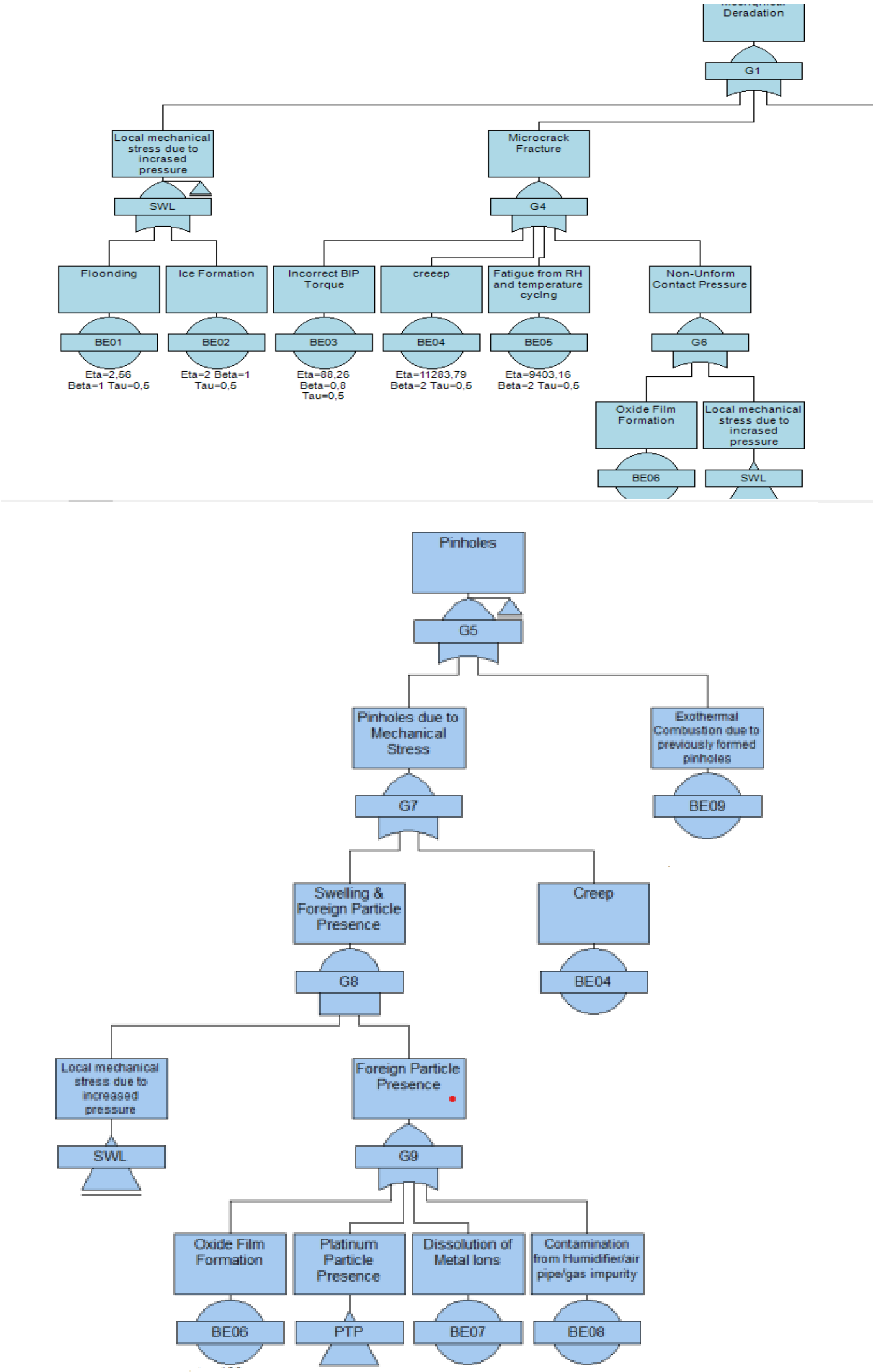


Figure 4-3 :Proposed `Membrane' FT Mechanical in isograph

The intermediate events of the sub-branch shown in Figure 8 include; ‘Local mechanical stress due to increased pressure’, ‘Microcrack Fracture’ and ‘Pinholes’. Any localised mechanical stress is caused by swelling inside the cell, and as such the swelling relationships detailed under the event ‘Local mechanical stress due to increased pressure’ are repeated in the ‘Microcrack Fracture’ branch as shown by the transfer symbol. Microcrack fractures can be considered to be anything that results in a physical breach of the membrane, and is segregated from pinholes due to geometry. Microcracks can be considered to be tears, whereas pinholes are circular holes. These are not grouped under one mechanical breach intermediate event due to the varying conditions and events leading to each phenomenon. The Pinholes section describes the basic events and combinations of events leading to the formation of pinholes on the membrane material. The two main pathways described are from either mechanical stress (such as punctures from foreign bodies) and a branch transferred in via the transfer gate (denoted by a triangle) labelled ’COMB’ in Figure 8 from the chemical degradation segment of the membrane FT. The branches ‘Chemical Degradation’ and ‘Thermal Degradation’ of the membrane were developed in a similar way.

8 Fault Tree Summary

The membrane is a single component which can experience failures from mechanical, thermal or chemical degradation mechanisms.

Quantification

Quantification of the FT was undertaken to gain an understanding of the expected failure occurrence during operating life.

$$F(t) = \frac{\beta}{\eta_d}\left(\frac{t-\gamma}{\eta_d}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta_d}\right)^{\beta}}$$

Where β is the shape parameter or Weibull slope, η_d is the scale parameter or characteristic lifetime, and γ is the location parameter. The shape parameter is equal to the slope of the line in a probability plot.

The location parameter, γ, is left at 0 for this study, as it is assumed that all degradation starts at the beginning of life for the cell.

Table 4-1 Table of Weibull distribution data used [101]

ID	Mu (t)	MTTR	Scale Parameter	characteristic lifetime,
	μ(t)	$\Upsilon(t)$	η_d	β
BE01	2.56	0.39	2.56	1
BE02	2	0.5	2	1
BE03	100	10^{-2}	88.26	0.8
BE04	10000	10^{-4}	11283.79	2
BE05	8333.33	1.2×10^{-4}	9403.16	2
BE06	32000	3.125×10^{-5}	36108.13	2
BE07	32000	3.125×10^{-5}	36108.13	2
BE08	228.83	4.37×10^{-3}	258.21	2
BE09	76.92	1.3×10^{-3}	86.80	2
BE11	76.92	1.3×10^{-3}	86.80	2
BE12	4	0.25	4	1
PREV	40	2.5×10^{-2}	35.30	0.8

If μ(t) follows a Weibull distribution with parameters βandηd then times to failure (T) will also follow a Weibull distribution with parameters β and η = Dfηd. Where Df is the degradation level at which failure occurs. In the analysis performed here, failure is assumed to occur when there is a 5% drop in voltage. Therefore, Df = 0.05Vin where V_{in} is the initial voltage of the cell. V_{in} is assumed to be 1 V for this work. [101]

Using the parameters η and β for T in the fault tree, enables the probability of the top event to be determined.

Each parameter calculated for each basic event is listed in Table 4, and shows the degradation rate, multiplicative inverse, scale parameter for μ(t), scale parameter for T, gamma function, and the shape parameter.

9 Results

- The lunched simulation for the top event … allows us to determine the unavailability evolution.
- Test time is not available for in this experimentation its why we tested 3 different values.
- 1st one test time =0

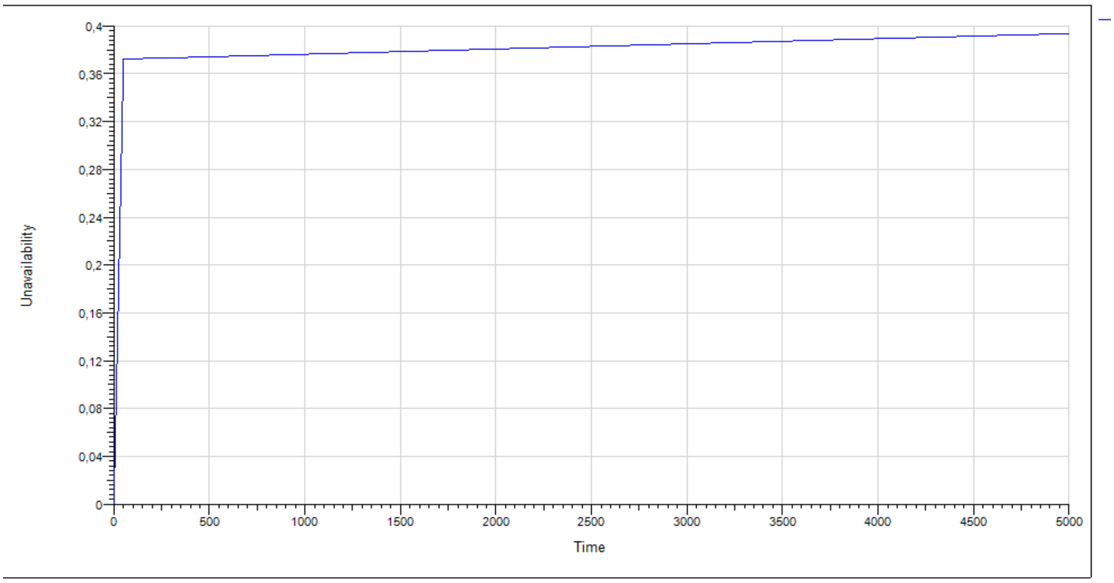


Figure 4-4 : graph that explains the life time of PEMFC in test interval =0

It shows the unavailability reaching 37% and continues to increase slowly during the life system.

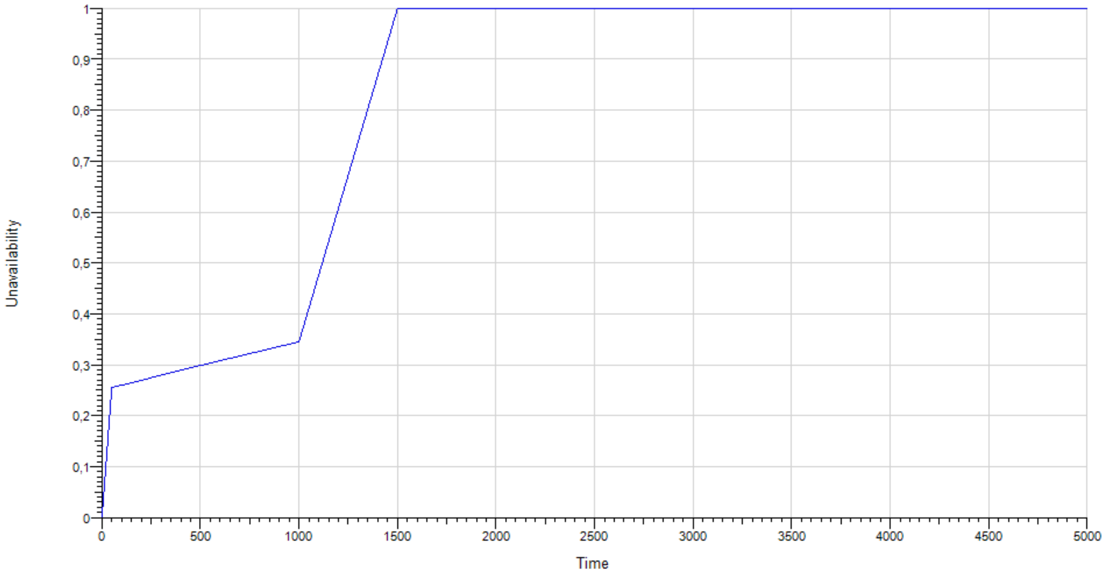


Figure 4-5 : graph that explains the life time of PEMFC in test interval =0.5

When the test interval is equal to 0,5 at the beginning the unavailability reaches 25% then after 1000 h it begins to increase significantly to reach 100% at 1500h

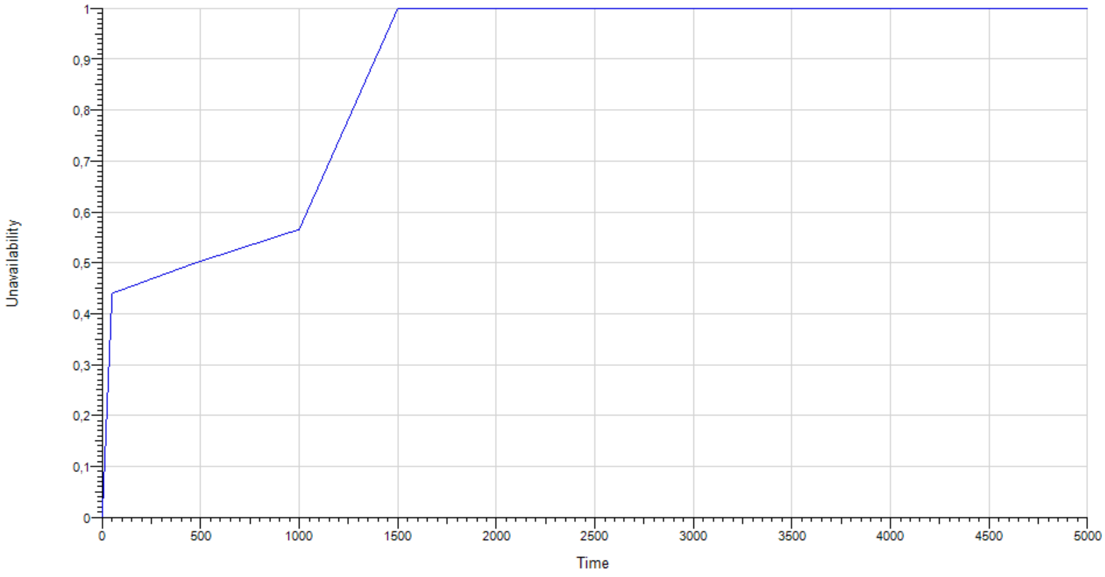


Figure 4-6 graph that explains the life time of PEMFC in test interval =1

When the test interval is equal to 1 at the beginning the unavailability reaches 44% then after 1000 h it begins to increase significantly to reach 100% at 1500h

10 Stopping Hydrogen Leaks

In principal, hydrogen leaks are stopped by tightening or replacing the leaking fitting or component.

Leaks must be remedied in a safe area where the hydrogen cannot accumulate and that is free of ignition sources., this is outdoors away from overhead obstructions, or inside a hydrogen-safe maintenance facility. Personnel should be limited to those fixing the leak. Smoking is strictly forbidden.

- Never *tighten* any fitting while it is under pressure; doing so could cause the fitting to shatter with serious personal injury. Never *loosen* a fitting while under pressure; doing so may cause the fitting or component to be propelled with extreme force

11 Conclusion

Many years of experience in the chemical industry and process technology have shown that hydrogen can be handled without technical safety problems arising. However, the people who currently have to handle hydrogen are experts or have received special training. If hydrogen is to be introduced as a motor vehicle fuel, large numbers of the general public will be confronted with this medium. Depending on the chosen storage technology, they will have to refuel their vehicles at filling stations with hydrogen either as a highly compressed gas or as an ultra-low temperature liquid. To prepare the way for handling hydrogen as a fuel, the public must be trained. In general, the risks associated with conventional fuels are underestimated and those associated with hydrogen overestimated. Just as every driver of a motor vehicle is now familiar with the basic rules of handling gasoline (petrol) or diesel oil safely, so the basic knowledge of how to handle hydrogen must be made generally familiar and applied in practice. If the specific properties of hydrogen are examined, it can be seen that a hydrogen fuelled vehicle offers a level of safety comparable with one that uses gasoline or diesel oil as its fuel.

With regard to vehicles' technical features, standards must be compiled that ensure safe and straightforward operation in all normally encountered conditions. In the event of abuse and in extreme situations, a high level of protection must still be available.

All hydrogen vehicles should comply with these standards. The relevant activities have already been commenced all over the world. It is important for the activities currently being undertaken in the USA, Japan and Europe to be coordinated and unified. “Hydrogen safety” must not prove to be a differentiating competitive feature.

Hence, although FTA can be seen as a tool to gain a greater understanding of how failure occurs in a PEMFC, and what basic events lead on to in a cell, it has limited use in reliability assessment as no useful quantification can be made. If a true understanding of the probability or frequency of failure is required, a different approach must be adopted.

Overall conclusion

Several facts are evident from this report. Hydrogen has been in widespread, large scale use for perhaps 100 years around the world, first as a lift gas in dirigibles and then as a fuel for spacecraft rocket engines. While there have been some very tragic and notorious accidents with hydrogen use, the dangers and phenomena are now generally understood and well recognized.

An example of this growth in understanding is that the airship Hindenburg accident report in 1937 cited a low value of the upper flammability limit of hydrogen in air, between 62 and 66%, which is now understood to be 74%. The Hindenburg event has become synonymous with a technological disaster, remembered by many as a terrible explosion. The facts show that the Hindenburg accident was one event in a long history of hydrogen airship accidents.

Nevertheless, the use of hydrogen as a chemical reagent and as a rocket propellant has grown to over 8 million metric tons per year. The public attitude about hydrogen must be changed by continued safe use to allow acceptance of hydrogen as a vehicle fuel. Changing attitudes will be difficult for many reasons; including the technical challenges of understanding unconfined combustion and explosion phenomena.

With proper precautions, hydrogen can be handled safely. No safety issues are foreseen that would warrant cessation of hydrogen use as a vehicle fuel. Important examples of handling safety are that NASA has stored and handled very large quantities of hydrogen safely in ground systems at spaceports for decades, and the small amount of hydrogen car operating experience to date has also been safe. Knowledge about hydrogen physical properties has increased, including accident modelling and prediction. Modelling of gas releases and gas mixing in enclosures is growing more and more detailed with the use of computational fluid dynamic computer codes. These models would be important to predict gas behaviour in natural- and forced-ventilation enclosures, such as underground parking garages, tunnels, residential garages, and passenger compartments of automobiles. Dealing with outdoor hydrogen releases is still a challenge for risk analysis, since it combines probabilistic techniques of predicting release location, breach size, and presence of ignition sources with the deterministic weather conditions occurring at the moment of release. The weather (wind speed, insolation, air temperature, etc.) will determine the hydrogen concentration in air. This probabilistic/deterministic complication is the main reason why some analyses assume the worst case detonation of gas in air to give an upper bound of consequences from a gas release event even though the likelihood of an open-air detonation event is quite remote. Detonation requires a strong ignition source (i.e., over ten thousand Joules of energy rather than a mill joule spark), a rich gas mixture in air, and generally some form of shock wave reflection that means confining the gas-air mixture in some way. A hydrogen-air deflagration can potentially “run up” to detonation if there is some confinement to reflect the combustion wave and the gas mixture is over 18.3% in air. Gas explosion experts generally agree that a gas deflagration, rather than a detonation, is the event that must be analysed following a postulated gas release

It is interesting to note that there have been some reports of hydrogen fires and deflagrations in the recent past. Some of these events can be attributed to the lack of knowledge by those working with the gas in cylinders or pipe work, lack of awareness that hydrogen gas was present, or improper control of the hydrogen in process equipment. Other events are simply due to equipment failure in close proximity to an adequate ignition source. While there are still mishaps with hydrogen in various industries, it is clear that hydrogen can be handled safely if its physical properties are understood and appreciated by those using the gas, and if proper precautions are taken. The design codes and regulations for hydrogen will play an important role in ensuring that precautions are in place to protect users, workers, the public, and the environment from the consequences of hydrogen events, and that these precautions would be maintained by routine inspection and maintenance of facilities. Work with improving codes for hydrogen gas usage is an important area to introduce hydrogen fuel safely into consumer usage.

The codes and standards needed to regulate hydrogen usage are in a very early stage of development, much earlier than is the case for methane (natural gas) or gasoline. The natural gas vehicle section in the Uniform Fire Code has duplicated the National Fire Protection Association’s standard on compressed natural gas vehicle safety into the code. Hydrogen codes and standards can be built upon from those in place for methane as a transportation fuel, since these are both lighter-than-air gases with low spark ignition energies for deflagration. Hydrogen codes and standards will have to take into account the unique physical, ignition and combustion characteristics of hydrogen gas.

Other areas of technology development that could be beneficial for increasing safety in hydrogen usage are design standardization so that fuel tank connections and refuelling station connections are uniform; engineering analysis of nozzle connections to promote low wear, easily operated connections; low cost, accurate hydrogen gas detectors; and improved hydrogen fire detectors. The standardized fuel connections mean refuelling without having to use an adapter, which would reduce mishandling and small leakage concerns. Connections that are easy to operate, seal securely and wear well would also reduce the occurrence of small hydrogen leaks during routine refuelling. Hydrogen gas detectors would be needed to protect enclosed spaces, just as natural gas detectors are presently recommended in the Uniform Fire Code for repair garages and other buildings. Hydrogen fire detectors typically operate by sensing ultraviolet or infrared wavelengths, since hydrogen fires typically do not give off visible light. These fire detectors are advanced technology, are relatively expensive, and can be susceptible to false alarms.

Hydrogen is a technically promising fuel for transportation. Testing experiences thus far have been positive. In particular, the hydrogen and fuel cell technology combination promises quiet, low emission power for automobiles, buses, industrial forklift trucks, and other vehicles as perspective, we proposed to analyse in deep other system component and in dynamic why using Bayesian approach for example.

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ABSTRACT:

Clarification of questions of safety represents a decisive contribution to the successful introduction of Vehicles fueled by hydrogen. At the moment, the safety of hydrogen is being discussed and investigated by various bodies. The primary focus is on fuel-cell vehicles with hydrogen stored in gaseous form. This thesis describes the safety concept of hydrogen-fueled vehicles with an internal combustion engine and Liquefied hydrogen storage. The fuel cell and hydrogen can be a solution in the development of zero-emission vehicles. Furthermore, because its combustion produces only water, the hydrogen could be considered as the fuel of the future.

The fundamental factor in the fulfillment of the requirements is an intelligent H_2 component layout in the vehicle. The aim of the crash program is primarily to protect the occupants, but also to ensure that the Hydrogen system develops no leaks.

Keyword;

hydrogen production; fuel cell electric vehicle; PEMFC; fuel cell; fault tree analysis.

Résumé:

La clarification des questions de sécurité représente une contribution décisive à la réussite de l'introduction des Véhicules à hydrogène. À l'heure actuelle, la sécurité de l'hydrogène est discutée et étudiée par divers organismes. L’accent est mis principalement sur les véhicules à pile à combustible avec de l’hydrogène stocké sous forme gazeuse. Cette thèse décrit le concept de sécurité des véhicules à hydrogène équipés d’un moteur à combustion interne et d’un stockage d’hydrogène liquéfié. La pile à combustible et l’hydrogène peut être une solution dans le développement de véhicules zéro émission. De plus, comme sa combustion ne produit que de l’eau, l’hydrogène pourrait être considéré comme le carburant du futur.

Le facteur fondamental dans le respect des exigences est une disposition intelligente des composants H_2 dans le véhicule. L'objectif du programme d'accident est principalement de protéger les occupants, mais aussi de s'assurer que le système Hydrogène ne développe aucune fuite.

ملخص:

يمثل توضيح مسائل السلامة ومساهمة حاسمة في الإدخال الناجح للمركبات التي تعمل بالهيدروجين. في الوقت الحالي، تتم مناقشة سلامة الهيدروجين والتحقيق فيها من قبل هيئات مختلفة. ينصب التركيز الأساسي على مركبات خلايا الوقود مع الهيدروجين المخزن في شكل غازي. تصف هذه الأطروحة مفهوم السلامة للمركبات التي تعمل بالهيدروجين مع محرك احتراق داخلي وتخزين الهيدروجين المسال. يمكن أن تكون خلية الوقود والهيدروجين حلا في تطوير مركبات عديمة الانبعاثات. علاوة على ذلك، نظرا لأن احتراقه ينتج الماء فقط، يمكن اعتبار الهيدروجين وقود المستقبل

العامل الأساسي في الوفاء بالمتطلبات هو تخطيط مكون ذكي لجزيى الهدوجين في السيارة. الهدف من برنامج التحطم هو في المقام الأول حماية الركاب و ضمان عدم حدوث أي تسربات لنظام الهيدروجين