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## **The State of the Art in Fuel Cell Condition Monitoring and Maintenance**

Michael Knowles<sup>1</sup>, David Baglee<sup>1</sup>, Adrian Morris<sup>1</sup> and Qinglian Ren<sup>2</sup>

<sup>1</sup>*Institute for Automotive and Manufacturing Advanced Practice, University of Sunderland, The Industry Centre, Colima Avenue, Sunderland, SR5 3XB, United Kingdom*

*E-mail: [Michael.knowles@sunderland.ac.uk](mailto:Michael.knowles@sunderland.ac.uk), [David.Baglee@sunderland.ac.uk](mailto:David.Baglee@sunderland.ac.uk), [adrian.morris@sunderland.ac.uk](mailto:adrian.morris@sunderland.ac.uk),*

<sup>2</sup>*Changan UK R & D Centre Ltd, No 1 Nottingham Science Park, Jesse Boot Avenue, Nottingham NG7 2RU, UK*  
*E-mail: [maggie.ren@changanuk.com](mailto:maggie.ren@changanuk.com)*

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### **Abstract**

Fuel cell vehicles are considered to be a viable solution to problems such as carbon emissions and fuel shortages for road transport. Proton Exchange Membrane (PEM) Fuel Cells are mainly used in this purpose because they can run at low temperatures and have a simple structure. Yet to make this technology commercially viable, there are still many hurdles to overcome. Apart from the high cost of fuel cell systems, high maintenance costs and short lifecycle are two main issues need to be addressed. The main purpose of this paper is to review the issues affecting the reliability and lifespan of fuel cells and present the state of the art in fuel cell condition monitoring and maintenance. The Structure of PEM fuel cell is introduced and examples of its application in a variety of applications are presented. The fault modes including membrane flooding/drying, fuel/gas starvation, physical defects of membrane, and catalyst poisoning are listed and assessed for their impact. Then the relationship between causes, faults, symptoms and long term implications of fault conditions are summarized. Finally the state of the art in PEM fuel cell condition monitoring and maintenance is reviewed and conclusions are drawn regarding suggested maintenance strategies and the optimal structure for an integrated, cost effective condition monitoring and maintenance management system.

*Keywords: Hydrogen Fuel Cells, Maintenance, Condition Monitoring.*

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### **1 Introduction**

Vehicle manufacturers are facing worldwide and regional challenges to meet the low-carbon agenda and reduce our dependence on fossil based fuels. Emissions reduction requirements will necessitate fundamental changes to the design of cars and the technologies they employ, Fuel cell vehicles (FCVs) are quickly becoming known as the alternative technology to conventional road vehicles and many manufacturers are embracing them as a future power source [1]. Many industries today view this area as an important source of economic growth, sustainable development and job creation. Fuel cells offer the advantage in transport applications of diminishing weight as fuel is expended

– a situation which does not apply to battery electric vehicles.

The relatively short life of PEM fuel cells is a significant barrier to their commercialization in stationary and mobile applications [2]. The performance of PEM fuel cells is influenced by many parameters including operating conditions and construction materials which influence the activation and mass transport losses [3]. Effectively monitoring and managing the operating conditions of PEM fuel cells and developing maintenance strategies will significantly improve the performance of fuel cell systems and prolong their life.

In this paper we will review the structure and properties of fuel cells and examine their advantages and disadvantages in vehicular applications drawing on reports of various trials [4][5][6][7]. The issues affecting reliability and lifespan will then be considered prior to an assessment of condition monitoring strategies and maintenance activities which can mitigate these issues. Modelling strategies are also described in terms of how they can support maintenance strategies tailored to the particular requirements of individual patterns of use.

## 2 Hydrogen Fuel Cells

### 2.1 Fuel Cell Structure

The most commonly used type of fuel cell is the Proton Exchange Membrane (PEM) Fuel Cell. The PEM fuel cell typically consists of two porous electrodes separated by a proton conducting membrane. The membrane is solid and is often ceramic. The membrane is impermeable to gases but will allow protons to pass through it. The electrodes are separated from the membrane by a catalyst [8]. The operation of the fuel cell and its components is described below.

In operation, hydrogen enters the cell on the anode side while oxygen or air enters on the cathode side. A catalyst on the anode side causes the hydrogen atoms to split into electrons and positively charge hydrogen ions – protons. The protons are able to travel across the membrane which creates a voltage across the cell. The electrons travel via the electrical circuit between the electrodes to reach the other side. At the cathode side, where there is also a catalyst, the electrons from the cathode, the hydrogen ions travelling across the membrane and the oxygen react to form water – the waste product. The lack of moving parts means that a well maintained fuel cell is typically extremely reliable.

Individual fuel cells are combined in use into a fuel cell stack. The stack structure is illustrated in figure 1.

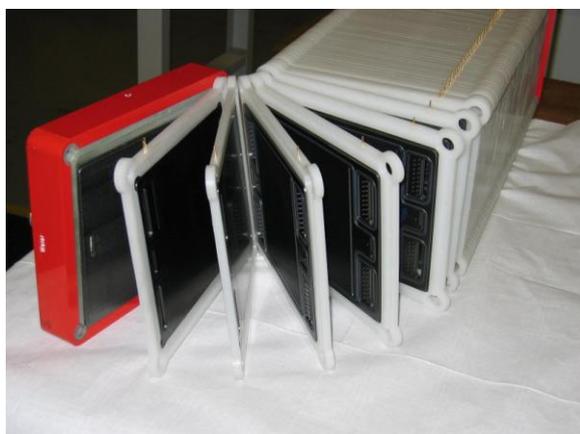


Figure 1: Fuel cell stack structure – each layer is an individual fuel cell.

The individual cells are combined in series with the cathode of one cell being connected to the anode of the adjacent cell. The key aspects of stack design in terms of long term efficiency and stability include [8]:

- Uniform distribution of reactants to and within each cell
- Ensuring the temperature of each cell is maintained at the correct level
- Ensuring there are no leaks
- Ensuring the stack is mechanically stable

A key aspect of this stack structure is that the performance of the stack is constrained by the performance of the worst performing cell [9].

A fuel cell stack also requires several support systems. It is necessary to ensure that hydrogen and the oxidant is delivered at the correct pressure, that water is removed at the correct rate and that the temperature is maintained at the correct level [8][9]. Therefore ensuring that these ancillary systems are maintained correctly is a key issue in fuel cell system maintenance.

### 2.2 Fuel Cell Applications in Transport

Due to the potential benefits of utilizing fuel cell technology for powering electric vehicles, a number of trials have been carried out. The University of Delaware has been operating 4 Fuel Cell powered buses since February 2007 [7] and has been investigating maintenance patterns and requirements as well as Cell Voltage Monitoring (CVM) systems [4]. A fleet of fuel cell buses were operated at the Shanghai Expo event in 2010 and were used to demonstrate a system of sensors and diagnostic algorithms [10]. Three fuel cell powered buses were introduced in Beijing as part of the clean public transport plan for the 29<sup>th</sup> Olympic games and have been used to investigate issues such as wireless monitoring and diagnosis [5][6] and degradation rates on particular routes [11]. The University of Birmingham has been using a fuel cell powered vehicle for delivering mail and for assessing the suitability of fuel cells for other duties [12]. Imperial College London have developed fuel cell hybrid racing vehicle which participated in the Formula Student race event in 2011. Finally, Ford Motor Co. has produced several fuel cell powered vehicles and has been using them to investigate both the performance and reliability of such vehicles but also the commercial viability [1].

## 3 Fuel Cell Reliability Issues

Reliability is seen as a key factor in ensuring that fuel cells cement a place as an alternative to the internal combustion (IC) engine. The Ford Motor Company has set a target for fuel cell vehicle's lifespan of 6000 –

8000 hours, equating to around 100,000 miles, and in initial trial vehicles have achieved up times of greater than 92% [1]. The US Department of Energy specify a lower lifespan of 5000 hours which they equated to 150,000 miles [13]. In a trial performed in Delaware, USA, a fuel cell/battery powered hybrid bus was out of service for 143 days in the space of two years due to stack damage and battery maintenance [7]. Clearly improvements in availability and maintenance requirements are needed if widespread penetration is to be achieved.

The effects of poor reliability are several. Firstly take up of fuel cell systems will be greatly reduced if reliability is seen as significantly poorer than that of proven technologies. Furthermore repairing fuel cells is a difficult operation which may require the stack to be sent for specialist attention. Additionally, parts of each cell, specifically the catalyst and membrane, are generally manufactured out of expensive and in some cases scarce materials. Thus ensuring that fuel cell stacks are in service for as long as possible is of critical importance. If fuel cell systems are to find widespread acceptance then ensuring that maintenance is considered at the design stage is essential.

Some limited work has been done examining Solid Oxide Fuel Cell (SOFC) reliability [14] and it has been found that the percentage voltage change rate drops linearly as impurity concentration increases. Some simulation work has been performed on PEM fuel cells [15][16][17][18][19][20], and models have been developed which can inform maintenance schedules and indicate the reduction of reliability over time [20]. The range of temperatures over which a fuel cell will operate is an important factor [13]. The effects of temperature on efficiency are already known [8]. The effect of temperature on reliability will be a key issue in successful commercialisation.

### 3.1 Fault Modes

Potential fault modes for fuel cells include: membrane dehydration, fuel/gas starvation, physical defects of membrane and catalyst poisoning. These are outlined in more detail in table 1.

Table 1: Fuel Cell Faults and Causes

Fault	Cause	Source
Dehydration/drying of membrane	Fuel not adequately humidified	[21][22]
Fuel/Gas Starvation	Flow variation in the electrode channels Flooding of electrode pores with liquid water	[21]
Hole(s) in membrane	Local hot spot	[21][9]
Fracture in membrane	Mechanical stress	[21][9]
Broken membrane	Incorrect pressure difference	[21]
Catalyst poisoning	Carbon monoxide	[23]
Hydrogen Leaks	Rupture of seals	[17]

Each of these fault modes is described in more detail in the following sections.

#### 3.1.1 Membrane dehydration

The performance of the membrane is critically linked to the water concentration within the membrane. The ability of the membrane to conduct protons is a strong function of water content [24][21][8]. Water transport across the membrane is affected by several factors which combine to determine the local water content. These mechanisms include water generation at the cathode, water molecules being dragged across the membrane by protons, diffusion due to concentration gradient across the membrane and permeation due to pressure difference across the membrane [8].

A crucial element in fuel cell design is the choice of membrane material which must meet various functional requirements in terms of proton transport, while being reliable and exhibiting long term endurance [25]. Current research is attempting to address these issues through the development of new membrane materials which are less demanding in terms of the conditions in which they work including hydration [26].

#### 2.1.2 Fuel/Gas Starvation

A number of causes exist for fuel/gas starvation. At the level of the entire stack, variations in channel flow resistance can cause fuel gas starvation. This can happen as a result of water formation, temperature variation or geometry deviations [21]. In terms of the individual cells within the stack, starvation can be

caused by electrode pores becoming blocked with water. This phenomenon is known as flooding and typically occurs on the cathode side where water is formed through the recombination and subsequent reaction between hydrogen ions, electrons and oxygen [8].

### 3.1.3. Physical Defects of Membrane

Physical defects of the membrane are caused by either mechanical stress or hot spots. Fuel cells used in transport applications are often prone to increased vibration and shock, and the effects of this are often neglected [27]. The resultant defects can lead to hydrogen and oxygen mixing in the cell and the occurrence of thermal combustion causing the leak to grow [4]. Research into membranes with superior physical durability is an area which is receiving attention [26].

### 3.1.4. Catalyst Poisoning/degradation

The dominant catalyst used in PEM fuel cells is Platinum. The performance of the catalyst can be degraded if it becomes poisoned by carbon monoxide [28]. This contaminant can be present in the fuel.

Table 2: Catalyst Poisons.

Anode	Cathode
Carbon dioxide (CO <sub>2</sub> )	Sulfur oxides (SO <sub>x</sub> )
Carbon monoxide (CO)	
Hydrogen sulphide (H <sub>2</sub> S)	Nitrous oxides (NO <sub>x</sub> )
Ammonia (NH <sub>3</sub> )	

Platinum alloys are increasingly used as the catalyst as a means of reducing the effects of catalyst poisoning [23]. The absorption of contaminants to the catalysts can be exacerbated by low operating temperatures [28]. Fuel and oxygen starvation are also major problems for fuel cell systems and can lead to degradation of the catalyst [29].

### 3.1.5. Hydrogen Leaks

The properties of hydrogen make it difficult to contain and thus fuel cell systems are prone to leaks. For this reason a certain leak allowance is always expected. An increase in leaks due to rupture of seals can, however, lead to a dangerous build up of hydrogen [17].

## 3.2 Long Term Implications of Faults

Allowing a fuel cell to run for an extended period of time can lead to permanent degradation and a reduction in efficiency and reliability. Excess water in the cell leading to flooding can cause a performance decrease in the electrodes, whereas dehydration of the membrane can lead to local hotspots causing damage to the membrane. Fuel starvation or catalyst poisoning can cause a decomposition of cell components causing permanent damage. Some damage such as that due to local hotspots or holes in the membrane can lead to a

temperature increase which can in turn cause damage other cells within the stack.

## 3.3 Reliability Modelling

It has been proved that PEM fuel cell systems can run for long periods of time but performance and reliability can suffer due to degradation of the catalyst and contamination of the membrane [17]. Several studies have attempted to model these effects. Tanrioven and Alam [20] describe a model of PEM fuel cell reliability based on a Weibull distribution. Reliability was analysed by Fowler et al [16] who observed that performance modeling was focused on brand new cells and little work had been carried out on reliability and long term performance degradation. A simplified electrochemical model was produced to provide a characterisation of performance at a given age. The causes of voltage degradation are identified as:

- Loss of catalytic activity
- Conductivity loss
- Loss of mass transfer of reactants

Mangoni et al [15] have developed a reliability model which is designed to account for uncertain operating conditions using a single parameter in stochastic simulations to inform maintenance scheduling. Frappe et al [30] have used numerical simulation to determine the benefits of fuel cell condition monitoring systems.

While the performance and reliability of PEM fuel cell stacks has been modeled under various stages of age, the effect of usage and the types of usage patterns to which stacks are exposed appears to have been neglected. Khayyer et al [31] identify and investigate the benefits in reliability from using two downsized stacks in the place of one larger system. Work such as this can utilise simulation and modelling to determine the optimal configuration for a particular stack.

## 4. Condition Monitoring

The fragility of fuel cell components and their disposition to further damage when operating under fault conditions means that condition monitoring is an area of enhanced interest. However systems such as that proposed by Zhan et al [32] which provide comprehensive condition monitoring of a variety of fuel cell systems are scarce. A number of systems and techniques for monitoring individual parameters and inferring other aspects of condition have been developed however.

Many current techniques for modeling the condition of PEM fuel cells involve the use of electrical measurements since these are easily taken without the need to modify the cell to include CM sensors. Many of these use equivalent circuit models of the fuel cell to

determine whether the cell is operating normally or within one of the potential fault modes. Ordonez et al [33] propose a system for monitoring the frequency response of a fuel cell, even when under load, to characterise cell condition.

Monitoring the hydration levels within the membrane is difficult since while it is possible to measure the relative humidity of the fuel and waste products, these do not relate to the membrane hydration in a straightforward manner. Fouquet et al [22] propose a system which measures the AC impedance of the cell and uses a model to estimate the cell hydration. Yousfi Steiner et al [34] describe the use of a neural network to estimate hydration levels based on easily measured parameters. Xue et al [21] describe a wide ranging model which uses the temperature and inlet/outlet pressure to establish an acceptable range for the output voltage. Lee et al [35] describe how impedance measurements can be used to provide prognostic information regarding condition and lifespan of the fuel cell. Onanena et al [36] propose the use of impedance spectra for estimating fuel cell operating time to inform maintenance strategies.

The importance of monitoring the individual cell voltages is highlighted by Rodatz et al [9] since detecting cell failures is difficult in a large stack due to the number of cells. Failure to detect a problem with an individual cell may mean the opportunity to remove the problem is lost due to the occurrence of permanent damage. The maximum current drawn from the stack should be limited to prevent the worst performing cells from being dragged to a negative voltage. Thus the worst performing cells limit the maximum power output of the stack [9]. Rubio et al [37] propose a system which uses electrical measurements to detect catalyst poisoning, along with membrane drying and cathode flooding, using electrical measurements. Brunnera et al [4] describe a system in use on the University of Delaware fuel cell powered vehicles which can detect anode flooding and air channel blocking in individual cells using relays to multiplex the many voltages being recorded.

In terms of detecting hydrogen leaks two routes are possible [17]. The first is to detect hydrogen itself using hydrogen sensors. These are, however, expensive so an alternative technique which involves measuring the mass flow at the anode is gaining popularity.

New sensor technologies, including nano-sensors have found many applications in condition monitoring systems. There are many ways in which these can be applied PEM fuel cell condition monitoring. New applications can be developed based on an analysis of the condition parameters whose measurement is most crucial to the long term operation of the system such as mechanical condition and membrane hydration. Kuo et

al [24] have developed flexible microsensors for non-invasive monitoring of temperature and humidity within a fuel cell stack. Lee et al [38] propose the use of micro-electro-mechanical systems (MEMS) sensors for in situ measurement of temperature and voltage.

## 4. Maintenance

Fuel cell maintenance in transport applications is an area of research which is still in its infancy. Valuable insight into the maintenance requirements of fuel cells is being acquired from the various applications trials, a specific example being the vehicle in operation at the University of Delaware [7].

A key factor in avoiding dehydration of the membrane is preventing electro-osmotic drag where hydrogen protons moving across the membrane drag water molecules with them. This can be avoided by ensuring the fuel is adequately humidified using a humidifier/heat exchanger [8]. Ensuring this system is maintained in full working order is a key maintenance task to ensure its operation is both effective and efficient.

Oxide coverage of the catalyst can be removed using pulses of high current. Several other operational techniques exist for maintaining the condition of the cells or dealing with temporary fault conditions, including a temporary reduction in load, increase in reactant flow (to remove excess water) and reduction of cell membrane to assist membrane hydration [9].

Various configurations of cooling system exist for fuel cell stacks. Coolants include deionised water, antifreeze solution or air and coolant can flow around the exterior of the stack or between the cells [8]. Cooling channels must be kept free of obstructions, and where a liquid coolant is used the level should be maintained. Maintaining the physical structure of the fuel cell is important to ensure there are no leaks in the stack [8][9] and to avoid membrane defects and leaks [17].

If fuel cell systems are to find widespread acceptance then ensuring that maintenance is considered at the design stage is essential. Many simulation models exist for fuel cell performance [18][18][28][39] Maintenance of support systems is also important since many of the problems uncovered in trials of fuel cell vehicles relate to the reliability of the support systems. Issues such as air intake cleaning and in the case of fuel cell hybrid systems, battery watering are seen as more significant issues than maintenance of the fuel cell itself [7]. What is not clear is whether this attitude is due to a 'replace when fail' approach to maintaining the cell stack.

As can be seen from the above discussion, there is no established protocol for the maintenance operations

which are required for a fuel cell stack. However the lack of moving parts means that fuel cells are, in themselves, capable of achieving high levels of reliability. As can be seen from the earlier analysis, many of the likely faults that can occur within fuel cells are the result of incorrect operation. One of the key facets of selecting suitable maintenance strategies will be fitting them to the usage patterns of the vehicles [11] and using tools and models to predict [10] and monitor [36] degradation rates under particular usage patterns.

## 5. Conclusion

It is clear that hydrogen fuel cell technology presents significant challenges in terms of managing reliability. It is entirely conceivable that these systems would not receive the commercial attention they are now subject to if it was not for environmental pressures, due to these difficulties. In order to achieve these environmental benefits it is crucial, however, that these issues are addressed.

Due to the potential for environmental benefits to be diluted by excessive or poorly managed maintenance, or by costly and preventable failures, condition based maintenance is a key tool which must be developed based on a thorough analysis of potential failure modes. Characterising cell failure modes often requires the use of multiple condition measures since two parameters are often needed to diagnose a particular problem, e.g. voltage drop in a particular cell when the hydrogen pressure is increased indicate a torn membrane in a particular cell. Successful implementation of fuel cell condition monitoring technology will be reliant on the correct selection of sensors.

The need to eliminate costly failures is a common driver across many technologies and is of particular importance for those whose development is being accelerated by environmental pressures for the reasons given above. Selection of the correct operating protocols is critically important to the reduction of failures and the increase of lifespan and reliability. Despite the technological complexity and economic barriers, the requirement for effective, well managed maintenance based on need and condition is one which fuel cells share with all technologies if we are to achieve a low carbon society.

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Mr Adrian Morris is operations manager at AMAP and leads the departments work in electric vehicle technology. Mr Morris has a background in quality management in manufacturing industries and previous appointments include APV, Black and Decker and the American Supplier Institute.



Dr Qinglian Ren achieved a PhD in Electric Vehicle Drive train design and worked on a variety of projects including Eco2Trans which achieved the conversion of electric buses to fuel cell power. Dr Ren now works at the Changan UK Research and Development Centre.

## Authors



Dr. Mike Knowles studied electrical and electronic engineering to PhD level at the University of Birmingham. Dr Knowles is now a postdoctoral research associate in AMAP. His research interests include condition monitoring, electric vehicle technology, intelligent software and maintenance management.



Dr. David Baglee achieved a PhD in Maintenance in 2005 and is now a project manager in AMAP. His research interests include maintenance and reliability management and condition monitoring. Dr Baglee has led a number of UK and European projects in these areas.