Developing RCM Strategy for Hydrogen Fuel Cells Utilizing On Line E-Condition Monitoring

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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 high maintenance costs and the inherent dangers of maintaining equipment using hydrogen are two main issues which need to be addressed. The development of appropriate and efficient strategies is currently lacking with regard to fuel cell maintenance. A Reliability Centered Maintenance (RCM) approach offers considerable benefit to the management of fuel cell maintenance since it includes an identification and consideration of the impact of critical components. Technological developments in e-maintenance systems, radio-frequency identification (RFID) and personal digital assistants (PDAs) have proven to satisfy the increasing demand for improved reliability, efficiency and safety. RFID technology is used to store and remotely retrieve electronic maintenance data in order to provide instant access to up-to-date, accurate and detailed information. The aim is to support fuel cell maintenance decisions by developing and applying a blend of leading-edge communications and sensor technology including RFID. The purpose of this paper is to review and present the state of the art in fuel cell condition monitoring and maintenance utilizing RCM and RFID technologies. Using an RCM analysis critical components and fault modes are identified. RFID tags are used to store the critical information, possible faults and their cause and effect. The relationship between causes, faults, symptoms and long term implications of fault conditions are summarized. Finally conclusions are drawn regarding suggested maintenance strategies and the optimal structure for an integrated, cost effective condition monitoring and maintenance management system.

1. Introduction
In recent years environmental concerns have lead to the accelerated development of a variety of new technologies. Such technologies are, in the main, concerned with either the generation or conversion of power or with improving the efficiency of existing systems. Electrical systems have received particular attention particularly in the area of generation since traditional techniques are highly polluting in the case of fossil fuel burning power stations or produce long term hazardous waste in the case of nuclear power generation. In addition to the development of static generating systems to replace fossil and nuclear based power stations small scale systems for electrical generation have become an area of interest particularly in transport applications. Static generation systems include wind turbines, solar panels and tidal generation systems while hydrogen fuel cells and super capacitors have received attention for electrical generation, conversion and storage in vehicular applications.
Low carbon technology developments in recent years can be classified according to whether they utilise existing technologies or apply new technologies. Hydrogen fuel cells fall into the latter category and use an electrochemical reaction to produce electricity from a supply of hydrogen and air. The materials involved in this process are in a state of constant evolution and the maintenance issues are yet to be covered for the complex electrochemical reaction which takes place. Fuel cells have found many applications in both static and mobile applications. Static applications include use in remote locations where connection to the power grid is difficult or impossible such as rural locations, military installations and satellites. Mobile applications include road transport which includes many pilot schemes involving fuel cell powered cars and buses, and submarines where fuel cells have many advantages over traditional propulsion technologies.

The rest of this paper is structured as follows. The following section provides a brief overview of fuel cell applications. This is followed by an overview of fuel cell operating principles, discussions of the maintenance issues related to hydrogen fuel cells and areas where condition monitoring can be applied. The paper is concluded with conclusions regarding the efficient management of reliability of this new technology.

2. Hydrogen Fuel Cells

2.1. Operating Principles

The most commonly used type of fuel cell is the Proton Exchange Membrane (PEM) Fuel Cell as illustrated in figures 1 and 2. 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 [1]. 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.

Figure 1. Individual fuel cell.
Individual fuel cells are combined in use into a fuel cell stack (Figure 2). 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 [1]:

- 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 [2]. The need for effective management and optimisation of fuel cell lifespan is strengthened by issues relating to the materials involved in constructing fuel cells. Parts of each cell, specifically the catalyst and membrane, are 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. 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 [1][2]. Therefore ensuring that these ancillary systems are maintained correctly is a key issue in fuel cell system maintenance.

2.2. Static Applications
Fuel cells have many advantages over conventional power sources in certain circumstances. In remote locations fuel cells have advantages over conventional fuel systems since they can be used in conjunction with solar panels and an electrolyser to produce hydrogen fuel from water. Systems such as this allow solar energy to be captured and stored as hydrogen allowing power to be delivered constantly. An example of such a system is the Stuart Island Energy Initiative where the surplus of solar energy is captured during the day and used constantly to power homes. The round trip efficiency (captured electricity – hydrogen – electricity) is in the region of 30 – 50% [3] which does not present an obstacle when sufficient solar energy is available to produce the electricity. Such systems also offer benefits for other off grid sites such as communication base stations and military installations.
2.3. Mobile Applications

The energy density of most battery types has been identified as the underlying difficulty in producing electric vehicles. The light weight of hydrogen coupled with the relative efficiency of fuel cell technology make fuel cells a viable alternative power source for electrically driven vehicles. An additional advantage is that hydrogen can be replenished in a much shorter time scale than batteries can be recharged. A major disadvantage of fuel cells is their inability to provide peak power requirements in vehicular applications. For this reason fuel cells are often used as part of a hybrid architecture alongside a battery. Examples of such a hybrid drive system include:

- The Honda FCX Clarity which uses a fuel cell as its primary power source, in conjunction with a 288v lithium ion battery which captures energy during regenerative breaking. The range is 280 miles per tank of hydrogen at 72 miles per kg on a combined cycle.
- The conversion of 2 buses to run on fuel cells performed by staff from the University of Sunderland. The Fuel cells provided power at 10kW. A battery system was used to augment this to a maximum of 25kW when needed.
- The fleet of Fiat Panda fuel cell/battery powered vehicles which recently participated in the ‘Challenge Bibendum’ event on mobile sustainability held by Michelin in Rio de Janeiro.

Dependability seen as a significant but solvable problem for the widespread development of fuel cell vehicles [4][5][6]. A survey of experts found that fuel cell vehicles could become fully commercialised within 10-15 years [6]. The Ford Motor company have set a target for fuel cell vehicles of a lifespan of 6000 – 8000 hours, equating to around 100,000 miles, and in initial trials vehicles have achieved up-times of greater than 92% [7]. The US Department of Energy specify a lower lifespan of 5000 hours which they equated to 150,000 miles [8]. 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 [9]. Clearly improvements in availability and maintenance requirements are needed if widespread penetration is to be achieved.

Fuel cells offer substantial benefits in other types of vehicle. The German and Italian navies each operate a number of fuel cell powered submarines. Fuel cells offer significant advantages over conventional power sources in such applications. Despite the fire and explosion concerns related to hydrogen, fuel cells offer lower risks than nuclear power systems and the lack of moving parts renders fuel cell powered submarines quieter and less detectable than those running on diesel. Based on the success of the German and Italian vessels, a number of other nations including Greece, South Korea, Pakistan and Turkey have invested in fuel cell powered submarines.

3. Hydrogen Fuel Cell Maintenance

3.1. Operational Requirements

The operational requirements and conditions of a fuel cell system will determine and limit the requirements and characteristics of its use. Table 1 gives an overview of the operational life required for economically viable application in various tasks.

| Application       | Operational Life Required (hours) |
|-------------------|-----------------------------------|
| Automotive        | At least 3000 to 5000             |
| Heavy duty trucks | Up to 20000                      |
| Stationary applications | Up to 40000                  |

A maximum rate of degradation ranging from 2 to 10 µV/hour is sought for the majority of applications which equates to an end of life power loss of less than 10% [10].

3.2. Fuel Cell Fault Modes
The construction of fuel cells makes investigation of internal condition difficult. Thus research into fuel cell operation and reliability analysis is reliant on simulation and modeling work. Simulation models allow the reliability of fuel cell systems to be investigated in order to provide insight into the maintenance requirements of the systems under various usage patterns. Models have focused on issues such as maintaining correct hydration levels, thermal management and hydrogen consumption. There has, however, been little work on integrating these models to provide a complete picture of fuel cell system performance, reliability and efficiency. Modeling work has, however, provided valuable insight into certain aspects of fuel cell operation in given operating conditions [11][12][13][14]. Reliability was analysed by Fowler et al [15] 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.

Fuel cell fault modes are summarized in table 2. One of the major factors in fuel cell reliability is maintaining the correct level of hydration. 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 [1]. Ensuring this system is maintained in full working order is a key maintenance task to ensure its operation is both effective and efficient.

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

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

3.2.1. 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 [1][16]. 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 [1].
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.

3.2.2. 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 [16]. 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 [1].

3.2.3. Physical Defects of Membrane. Physical defects of the membrane are caused by either mechanical stress or hot spots. Such defects can lead to hydrogen and oxygen mixing in the cell and the occurrence of thermal combustion causing the leak to grow [2].

3.2.4. Catalyst Poisoning. 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 [17]. This contaminant can be present in the fuel. Other poisons are listed in table 3.

| Anode                          | Cathode                          |
|--------------------------------|----------------------------------|
| Carbon dioxide (CO₂)           | Sulfur oxides (SOₓ)              |
| Hydrogen sulphide (H₂S)        | Nitrous oxides (NOₓ)             |
| Ammonia (NH₃)                  |                                  |

Platinum alloys are increasingly used as the catalyst as a means of reducing the effects of catalyst poisoning [18]. The absorption of contaminants to the catalysts can be exacerbated by low operating temperatures [17].

3.2.5. 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 [19].

3.2.6. 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 to other cells within the stack.

3.3. Fuel Cell Condition Monitoring. 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. Monitoring the hydration levels within the membrane is difficult. 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. Many systems use equivalent
circuit models of the fuel cell to determine whether the cell is operating normally or within one of the potential fault modes. Ramshak et al [10] propose the use of electrical measurements and impedance models to determine water content to avoid permanent damage due to drying. Fouquet et al [20] propose a system which measures the AC impedance of the cell and uses a model to estimate the cell hydration. Xue et al [16] describe a wider ranging model which uses the temperature and inlet/outlet pressure to establish and acceptable range for the output voltage.

The importance of monitoring the individual cell voltages is highlighted by Rodatz et al [2] 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 [2]. Rubio et al [21] propose a system which uses electrical measurements to detect catalyst poisoning, along with membrane drying and cathode flooding, using electrical measurements.

In terms of detecting hydrogen leaks two routes are possible [19]. 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. We believe there are many ways in which these can be applied to PEM fuel cell condition monitoring. New applications can be developed based on an analysis of the condition parameters whose measurement are most crucial to the long term operation of the system such as mechanical condition and membrane hydration.

4. Application of Reliability Centred Maintenance to Fuel Cell Maintenance Management

Reliability Centred Maintenance (RCM) is a method for determining the maintenance needs of a particular asset, component and sub-component. The focus of RCM is on maintaining system function rather than restoring equipment to an ideal condition Moubray [22]. RCM allows the maintenance ‘team’ to identify the critical components, their function and failure modes, therefore identify failure patterns and possible maintenance tasks to maintain operation. RCM, according to Ben-Daya [23] is characterised by the following features:

- Greater safety and environmental protection, due to improved maintenance.
- Improved operating performance, due to more emphasis on the maintenance requirements of critical components.
- Greater maintenance cost-effectiveness, due to less unnecessary maintenance.
- A comprehensive maintenance database, which reduces the effects of staff turnover with its attendant loss of experience and expertise.

These features align with the requirements for fuel cell maintenance in terms of prioritizing safety and cost. RCM is described by Chan et al [24] as a maintenance methodology that allows a progressive logical approach based upon the collection and analysis of basic equipment data. The primary reason for the development of RCM is to implement a preventive maintenance strategy that could adequately address system availability. RCM is, however, time consuming and applying a full-blown RCM methodology requires large amounts of data, including historical data which may not be available. In addition, RCM, according to Pintelton et al [25] can improve system availability and reliability and increase safety. The main stages of the RCM methodology involve determining the answers to the following questions:
What is the function of the equipment?
What causes each functional failure?
What causes each failure and identify failure modes?
What is the failure effect?
What is the consequence of each failure?
What proactive task(s) should be done to predict or prevent each failure?
What default action should be done to if a suitable proactive task cannot be found?

Each component in a fuel cell system needs to be monitored to detect any abnormalities before they develop into potential problems. Currently due to the small size of certain fuel cell applications and the often remote and inaccessible locations they operate within, it can prove difficult to monitor each and every component. Therefore using RCM will allow for the critical component(s) to be identified and the appropriate maintenance, or mix of, maintenance strategies developed and implemented.

Application of the principles of RCM is believed to be a key component of successful implementation of effective fuel cell maintenance for the following reasons:

- Identification of ‘critical equipment’.
- Defines the function and allows specific operating parameters to be set.
- Aims to preserve system functions, rather than preserving equipment using specific technologies.
- The application of such technology may be seen as unproven in this context. A detailed RCM analysis will form the basis of a business case since it ties any investment to where it is most needed.

Unlike other maintenance techniques, RCM does not attempt to prevent all failures, it allows the consequence of failure to be identified and, depending upon severity, develop a maintenance strategy which is ‘unique’ to that particular fault.

5. Application of E-Maintenance to Fuel Cell Maintenance Management

Recently, the growth of wireless communication technology, mobile technology and web technology has increased at an immense pace. Maintenance personnel are no longer restricted to “pen and paper” to determine maintenance tasks and review maintenance work orders. Recent trends have shown that improved connectivity, faster transfer of data and the ability to store and analyze large amounts of data is now required by maintenance managers. Current e-maintenance tools have already utilized existing web and computing network technology to form a maintenance infrastructure for integrating and synchronizing various maintenance information which supports and enhances collaboration between different users [26].

E-maintenance is not a collection of different models and techniques, it is a system which needs to be incorporated with other systems which help collect, analyse, and define a set of maintenance tasks which utilises the concept of the “right data, to the right person at the right time”. E-maintenance relies on tools and techniques from a variety of different sources to provide data, and if possible historical data. Recently PDAs have been used to collect and store trends in maintenance, failures and consequence of failure.

The role of the PDA is to provide a user-friendly, comfortable and powerful mobile computing device for dealing with different types of data processing and maintenance activities [27]. The role of RFID smart tags is to support the asset management and maintenance activities. Unlike other
maintenance technologies, the use of RFID and PDA together for maintenance is established on the concept of helping workers perform their maintenance tasks faster, easier and more accurately and to avoid any improper maintenance activities and also improve security and safety. During maintenance, tags information can be retrieved and provide the information required for online querying. However, RFID systems often do not work efficiently in ‘difficult’ environments such as high electromagnetic interference, high/low temperature and presence of liquids and metal surfaces. All of which exist within fuel cells. The aim is to develop a RFID tag which can withstand the environment found with fuel cells while maintaining data storage and data transfer integrity.

Increasingly mobile phone technology and capability has converged with that of PDAs. So-called ‘smart-phones’ are available at relatively low cost and offer the ability to run easily-written software. Furthermore they are increasingly equipped with high level systems such as GPS receivers and broadband connectivity. Smart-phones also feature calendar and organizer systems which can be integrated with bespoke software. These features, coupled with steadily growing memory capabilities make smart-phones the likely replacement for PDAs as mobile maintenance management tools, especially in applications where remote maintenance is required due to their mobile connectivity.

6. Conclusions

If hydrogen fuel cells are to find widespread acceptance then it is essential that their lifespan is maximised through effective management of operational conditions and through the provision of appropriate maintenance activities. The wide range of conditions under which fuel cells operate means that maintenance and operation need to be tailored to the application in question. Modelling the operation and maintenance needs of fuel cells is a crucial step towards achieving these objectives. Furthermore condition monitoring solutions should be scaled to application, geared towards detecting problems and reducing load before permanent degradation occurs.

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 that these issues are addressed.

To support maintenance strategy development for Fuel Cells e-condition monitoring tools and techniques need to be utilised. Appropriate and safe task selection needs to be developed supported using mobile-devices such as PDA and RFID. The combination of e-condition monitoring and mobile data collection and analyses devices will provide the maintenance engineer the necessary information and application required to carry out maintenance on Fuel Cells in an effective and safe way.

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