PORTABLE POWER APPLICATIONS OF FUEL CELLS

ETSU F/03/00253/00/REP

DTI Pub Urn no 02/1493

Contractor
QinetiQ

Prepared by
Michael Weston
Jeremy Matcham

First published 2002

I EXECUTIVE SUMMARY

Objective

The objective of this report is to evaluate the current technical status of fuel cell technology with respect to their suitability for portable power applications. This has been achieved by focusing on the present capabilities of UK companies and academe and highlighting areas in which the UK is in a strong position, globally, and conversely those in which the UK is weak. From this, recommendations have been drawn illustrating the necessary measures required to enhance UK prospects and competitiveness in the future.

Background

Within the last few years the development of fuel cell systems for portable and remote power applications has received considerable attention. This is because the contemporary battery technologies, although technically well developed and commercially ubiquitous, still suffer from certain limitations particularly with regard to energy density, lifetime, and environmental considerations. Fuel cells offer a unique combination of efficiency, flexibility and reliability that can be superior to the existing battery packs used in today's consumer electronics.

In particular, this upsurge in interest has been stimulated by the recent successes reported for the application of PEM fuel cell technology to small-scale power applications (<500W). The transfer of such technology into consumer devices has unfortunately been limited by the need for a safe and portable source of clean hydrogen. While research into hydrogen generation and storage continues, some developers have contemplated using alternative hydrocarbon fuels, such as methanol or natural gas. This either necessitates the use of micro-reformer technology or different fuel cell systems (SOFC, DMFC) both of which themselves require considerable development before reaching commercialisation.

In more general terms, if fuel cells are to be successfully incorporated into electrical devices several technological challenges relating to miniaturisation need to be overcome. These are mainly associated with thermal and water management which, for larger scale applications can be addressed by ancillary systems such as heaters, humidifiers and pumps. For the more size and weight critical portable power applications such peripherals must be reduced in size, or eliminated, and optimised for parasitic power consumption without degrading performance.

Approach

A review of the available literature concerning the status of fuel cell technology with particular regards to its readiness for portable applications was undertaken. The extent of this search, drawing from both paper and electronic media covered scientific publications, conference proceedings, company literature and private communications with relevant individuals. The review was broken down into a number of steps relating to different aspects of fuel cell development.

Outcome

The technology status review indicated that the PEMFC system has generated considerably more interest than either of its rivals, and presently has the greatest potential for application in this case. While this technology is more advanced there are still many issues relating to fuel choice and catalyst design that require further examination, however much of this work is currently undergoing significant development. Benefiting directly from the success of PEM technology, the DMFC, while still an emerging technology has shown itself to have excellent potential if certain issues relating to the conducting membrane can be resolved. SOFC technology in its current state of development is less applicable to portable power applications. This is due to the high temperature of operation and the low power density of the more advanced tubular form. This may change as planar technology undergoes more development but this is a longer term option.

These observations are supported by the list of products, which is dominated by PEM based devices. The currently available products are generally large and heavy although the next generation of devices undergoing development promise significant reductions in both size and weight. It proved difficult to obtain accurate information regarding the price of these units and what little data was available indicated that at present, due to their low-volume production, they are far from cost-effective alternatives. A major limiting factor is presently the fuel storage since no ideal source of hydrogen has yet been developed for portable applications, although catalytic borohydride decomposition appears promising. The other existing technologies do not efficiently scale down to the portable level. While there is scope for micro-reforming technology it is still in the early stages of development. Methanol storage is not so problematic but the crossover problem necessitates a large store of water, to allow dilution, which adds to system size and weight.

It is therefore not surprising that the main obstacles to market penetration are size, weight and the cost. These obstacles severely limit the possible routes to the portable power market and it is difficult to highlight any potential niches open for exploitation. While a quieter, more-efficient power source offers many benefits over the existing internal combustion engines eg camping generators it seems unlikely that the majority of users would be willing to pay a significant premium. Similar benefits over battery technology are not immediately obvious to the consumer who is likely to be unaware of the pollution caused by batteries in landfill sites. Even with good environmental reasons further incentives are probably required although unlike vehicle systems it is difficult to mitigate the costs through leasing or tax breaks for small electrical goods. At present the main market for fuel cells, at least in the UK, is mainly internal, in that the primary customers are other manufacturers or parties interested in experimenting with the technology. However a lowering of costs combined with the push for cleaner, "greener" power generation may offer future opportunities.

These improvements are unlikely to come from within the UK as it presently stands since it has a comparatively small number of fuel cell developers. While these developers have impressive track records and are delivering quality research the lack of a home market for portable power and significant competition overseas limits their potential.

Conclusions

At present fuel cells are too costly and tend to be too large or heavy to be a suitable replacement for the batteries already used. The cost is primarily a factor of the hand-made nature of existing systems and thus there is scope for major reductions through the application of mass production techniques. While the use of platinum catalysts in PEM and DMFC systems has a significant effect on cost this can be mitigated through recycling. The fuel cell size is constrained by the need to control the mass and thermal transport through the correct choice of flow fields and separator plates. Significant minimisation of these components requires a new set of techniques that are potentially offered by micro-technology solutions, which are currently undersubscribed within the UK.

The lack of a suitable fuel infrastructure contrasts poorly with the existing national electricity grid. Similarly the drawbacks with the storage or generation of hydrogen at the portable level are limiting when compared with an established battery system. However if the future hydrogen economy is realised for transport or distributed generation then this will support the application of fuel cell technology in portable devices.

Recommendations

While it would be possible to wait for the eventual installation of the hydrogen economy before considering portable applications it would be better to facilitate this process. To further these ends a number of recommendations have been proposed and briefly listed here: stimulate research into micro-technology by supporting the collaboration of fuel cell developers and the manufacturers of portable devices; support research into hydrogen storage technology, as this is presently a major obstacle; indicate benefits and safety of such systems through high profile demonstrator programme; continue support of the advancement of the underlying technology by academic and industrial research; investigate incorporation of electrolysers into existing energy framework.

Fuel cell technology is continually and rapidly advancing and developers have already found solutions to a number of difficult problems. While the present market conditions are not entirely suitable for the current generation of fuel cells it seems likely that changing consumer demands, environmental considerations and the pace of fuel cell research will lead to their commercial viability.

II LIST OF CONTENTS

III LIST OF TABLES

1 INTRODUCTION

This report will address the present and future suitability of fuel cell technology for portable applications. It will begin by removing potential confusion over terminology by clearly stating its terms of reference. Following this a review of the current technological status will be presented for each fuel cell system. A number of possible applications will be examined for market potential focusing on the benefits that fuel cells could offer. The main players capable of delivering this technology to the market will be examined and issues that will adversely affect market entry will be highlighted. Conclusions based upon this information will generate research priorities leading to the mitigation of these issues.

This document contains information regarding the world-wide status of portable-scale fuel cell technologies, and is based upon public-domain information retrieved up to the date of publication. The principal information resources for this document have been the Internet, symposia and conference proceedings publications. The information presented herein is the authors own interpretation of the information extracted from these resources.

1.1 Terms Of Reference

1.1.1 Market Opportunities For Portable Fuel Cells

This report will be confined to applications, which are of a size and weight to be comfortably portable, by the user. The power source will be used in situations were there is either no connection to mains electricity or such a connection would impair operation of the device. Good examples of these are given by mobile phones, for the former, and power tools, for the latter.

Table 1 indicates possible applications areas for portable fuel cells that define certain power bands. A description of each of these will be given in the market section.

It is also worth considering the general forces driving changes in the market that could be exploited to aid integration of fuel cell systems. These forces stem primarily from customer inconvenience caused by the need to frequently recharge batteries or carry replacements. This restricts mobility and that is the key selling point for portable devices.

1.1.2 The Application Spectrum - Pocket Power To Portable Fuel Cell Products

It is obvious that fuel cells intended for integration within such common hand-held devices as electronic notebooks, laptop computers and mobile telephones, really do need to be compact and lightweight in order to satisfy the “hand-held” criterion. In meeting this criterion, fuel cells tend to be either miniaturised versions of larger, open-cell, stacked plate devices, or of a radically different “flat-plate” or “planar” design. These latter devices are intrinsically open-cell and more amenable to fabrication using lithographic techniques (as used in the manufacture of silicon-chips).

Next in line from the hand-held device is the “portable power supply” fuel cell. Such devices would, generally, be carried in a separate package to the device that they are intended to power, but need not be restricted to powering only one, custom-designed device. Consequently, all products from mobile telephones through to small portable power tools could be adapted to use such power supplies. The idea of using these as a means of re-charging the batteries in existing mobile gadgets is common within the fuel cell industry.

Moving along the portable “spectrum” still further sees an array of devices that can be transported from location to location by hand, but would be left in one place during operation. Such devices include portable power supplies for out-door and camping uses and educational or promotional display units. There is, commonly, more precise and abundant product information available for these power supplies, and their early presence on the commercial market may have much to do with the reduced criticality of packaging volume constraints. Both open-cell and closed-cell stacks have found application in this range of product.

At the higher-power end of the portable device spectrum there are power supplies that are more likely to be transported by vehicle to a remote destination to be left “in the field” to power remote data logging and telecommunication equipment. Included within this category are a few low-power-vehicle propulsion devices, which could be considered as “self-portable” devices - offering no other purpose but to propel themselves and the operator form location to location. Low-power vehicles, as such, include wheelchairs, power-assisted bicycles, scooters, pleasure boats, electric carts and luggage/pallet trolleys.

2 PRESENT STATUS OF FUEL CELL TECHNOLOGIES

2.1 Fuel Cell Companies

A survey has been made of prominent organisations involved in the research and development (R&D) and manufacture of fuel cell devices that produce a power output in the range from <100mW to ≈500W. This data has been split into three tables (Appendix A):

- *Commercial Products Available:*
  Organisations displaying public-domain product information, and indicating that orders can be taken for their products, have been placed in this category. No further comment can be made on the delivery time for the products or the production capacity for the products.

- *Commercial Products in Preparation:*
  Organisations indicating that they are currently developing commercial-scale manufacturing capabilities for a demonstrated device or system has been placed in this category. No further comment can be made on the time-scale for production developments

- *Products in R&D or Demonstration Phase:*
  Organisations publishing information regarding R&D efforts into the development of devices with a possible commercial application, or have demonstrated such a device, have been placed in this category

2.2 Fuel Cell Technical Status

2.2.1 Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

The PEMFC is the most developed fuel cell system[1]. It is currently being considered for a number of applications within the transport and distributed power spheres. The main acknowledged technical drawback of the system is the poisoning effect of small amounts of carbon monoxide on the platinum catalysts. This has been mitigated to some degree through continual research and inventive design but in general pure hydrogen is the preferred fuel. This is perhaps the greatest commercial problem since, until a suitable hydrogen infrastructure becomes available, such systems are dependant on either stored hydrogen or reformed hydrocarbons both of which are not trivial issues. Another possible commercial disincentive is that the levels of platinum catalyst used lead to an associated rise in overall cost.

At the heart of every PEMFC stack is a single MEA (membrane electrode assembly) which is comprised of -

- the porous gas diffusion electrodes (anode and cathode),
- the proton conducting electrolyte membrane,
- anodic and cathodic catalyst layers, which are mostly deposited on the relevant electrodes although have been deposited on the membranes in some recent work.

These MEAs are sandwiched between bipolar plates, which act as current collectors and reactant flow fields, to produce a stack. These stacks can be connected in series or parallel depending on the voltage or current requirements of the particular application.

The choice of catalyst ensures that the electrode reactions are facile at low temperatures. This allows a greater range of lightweight materials to be available for cell construction and minimises the heat balance problems suffered by higher temperature systems and offers a fast start capability. The cell also is able to sustain operation at higher power densities than any other type of fuel cell. Other beneficial attributes of the cell include no corrosive fluid hazard and lower sensitivity to orientation. As a result, the PEMFC is particularly suited for a range of applications.

The lower operating temperature of a PEMFC results in both advantages and disadvantages. Low temperature operation is advantageous because the cell can start from ambient conditions quickly, especially when pure hydrogen fuel is available. It is a disadvantage in that expensive platinum catalysts are required to promote the electrochemical reaction. Carbon monoxide (CO) binds strongly to platinum sites at temperatures below 150^{o}C, which reduces the sites available for hydrogen chemisorption and electro-oxidation. Because of CO poisoning of the anode, only a few ppm of CO can be tolerated with platinum catalysis at 80^{o}C. Since reformed hydrocarbons contain about one percent of CO, a mechanism to reduce the level of CO in the fuel gas is required. One technique is to inject a small quantity of oxygen into the contaminated hydrogen stream to rapidly oxidise CO adsorbed onto the catalyst surface. Cells incorporating such air bleed systems have been successfully demonstrated on fuels containing 100ppm of CO without any degradation in performance compared to pure hydrogen. However oxygen bleeding risks the formation of hot-spots which can hasten the development of pin-holes in the membrane and the excess of injected oxygen left after the CO is removed will react with hydrogen reducing coulombic efficiency.

Another critical requirement of these cells is maintaining a high water content in the electrolyte to ensure high ionic conductivity and hence a low resistance to current flow, which increases overall efficiency. The water content in the cell is determined by the balance of water production at the cathode and its transport during the reactive mode of operation. Contributing factors to the water transport include electroosmotic drag through the cell, back diffusion from the cathode, the diffusion of any water in the fuel stream through the anode and entrainment from both gases through the cell. The water transport is a function of the cell current and the characteristics of the membrane and the electrodes.

The primary focus of ongoing research is to improve the performance of the cell and lower its cost[2,3]. The principle areas of development are improving cell membranes[4]; handling the CO in the fuel stream; and refining electrode design. Other sulphonated fluorocarbon polymer membranes as well as a number of different supports and deposition techniques have been investigated and shown improvements in performance over Nafion. The sensitivity to CO has been mitigated by the improvement in catalyst design with the development of Pt/Ru anodes. Through optimisation of the catalyst and electrode structure the catalyst loadings have fallen from four, as used in the original Gemini cell, to as low as ~0.2mg/cm^2 while still maintaining power densities in excess of 0.7W/cm^2. Such advances have allowed power densities of 1.5kW/l to be achieved in pressurised systems, however even without these ancillaries the power densities (~0.3kW/l) are still capable of bettering the competing fuel cell systems.

There has been an effort to incorporate system requirements into the fuel cell stack in order to simplify the overall system. This work has included a move toward operation with zero gas humidification at ambient pressure and direct fuel use.

2.2.2 Solid Oxide Fuel Cells (SOFCs)

Despite almost one hundred and fifty years of intermittent research SOFCs are only now approaching commercialisation. This delay can be attributed to the problems encountered with gas tight seals at the high temperatures required. While tubular systems circumvented these problems to some degree their inherent poor power density limited their commercial appeal. However the advantages of the high grade waste heat generated by these systems for fuel reforming or co-generation applications attracted a steady stream of research[5]. Planar systems have recently become more viable through advances in materials and thin film technologies[6]. These are more commercially interesting since their increased power density and fuel flexibility offers an alternative to PEMFC systems in certain applications. However even in these systems the operating temperature remains high which has obvious disadvantages in small, portable applications.

2.2.2.1 Tubular SOFC

One great advantage of the tubular design of SOFC is that high temperature gas-tight seals are eliminated. Each tube is fabricated like a large test-tube, sealed at one end. Fuel flows along the outside of the tube, towards the open end. Air is fed through a thin alumina air supply tube located centrally inside each tubular fuel cell. Heat generated within the cell brings the air up to the operating temperature. The air then flows through the fuel cell back up to the open end. At this point air and unutilised fuel from the anode exhaust mix and are instantly combusted so the cell exit is above 1000^{o}C. This combustion provides additional heat to preheat the air supply tube. Thus the tubular SOFC has a built in air preheat and anode exhaust combustor, as well as requiring no high temperature seals. Finally, by allowing imperfect sealing around the tubes, some recirculation of anode product gas occurs allowing internal reforming (the anode product contains steam and CO_2) of fuel gas on the SOFC anode.

2.2.2.2 Planar SOFC

Alternatives to the tubular SOFC have been developed for several years, notably several types of planar configuration, and a monolithic design. The planar configurations more closely resemble the stacking arrangements described for the PEMFC. This bipolar or flat plate structure enables a simple series electrical connection between cells without the long current path typified by the tubular design. The bipolar flat plate design thus results in lower ohmic losses than in the tubular arrangement. This leads to a superior stack performance and a much higher power density. Another advantage of the planar design is that low-cost fabrication methods such as screen-printing and tape casting can be used. One of the major disadvantages of the planar design is the need for gas-tight sealing around the edge of the cell components. Using compressive seals this is difficult to achieve and glass ceramics have been developed in an attempt to improve high temperature sealing. Similarly, thermal stresses at the interfaces between the different stack and cell materials may cause mechanical degradation so thermal robustness is important.

2.2.2.3 Current Status

Siemens Westinghouse have successfully demonstrated their tubular SOFC technology for record breaking operating times of 20,000 hours plus[7]. This has shown the reliability and lack of maintenance required for systems of this type. The design of the tubular system is constantly evolving and the latest high-density tubes[8] offer state of the art power densities (~300W/m^3). Unfortunately these power densities are still much too low for any application that is volume restricted. Thus applications for these systems remain limited and in general at the higher end of the scales considered for portable power (500W+).

Adelan a spin-off company utilising the technology developed by Kevin Kendall (now of Birmingham University) is perhaps the UK's primary developer of small scale tubular SOFC systems. As with many other companies they have been working on auxiliary units for truck cab power, a technology that offers considerable savings when compared to the fuel consumption through engine idling. The power requirements for such an application are in the 3kW range, beyond the scope of this report, but smaller units based on this technology have been considered for 'self-portable' applications such as electric trolleys and small carts.

2.2.2.4 Summary

Lower temperature (~600^{o}C) planar systems are only now approaching mainstream commercialisation and will in the main be competing directly with tubular technology in such areas as distributed power generation (10kW to 300kW). Thanks primarily to the high operating temperature it is difficult to imagine where this technology can be applied to portable applications a point that is strengthened by the lack of available demonstrators or prototype units. Perhaps the next generation of intermediate temperature SOFCs will be more applicable to smaller scale applications but at present the long start up times and elevated operating temperatures limit them to the kilowatt and above range. Future planar systems offer potential to go below this but operational data is currently limited.

2.2.3 Direct Methanol Fuel Cells (DMFCs)

An offshoot from solid polymer technology the Direct Methanol Fuel Cell (DMFC) seemingly offers certain advantages that make it particularly applicable to portable power applications. The direct use of methanol (or similar liquid fuels) as a fuel has been considered as an alternative to hydrogen in polymer based systems. It simplifies fuel storage issues and since methanol contains more energy in comparison than the current battery technologies it can offer greater operating times. While direct methanol utilisation has been successfully demonstrated in the laboratory fuel crossover, where the methanol is dragged through the membrane polarising the cell and poisoning the cathode catalyst, reduces power density and possibly exposes the user to toxic fumes. While methods to limit this effect have been developed[9] they are currently not technically satisfactory having adverse consequences on overall power density.

The structure of the DMFC is a composite of two porous electrocatalytic electrodes on either side of a solid polymer proton conducting membrane. The thermodynamic reversible potential for the overall cell reaction is 1.214V, which compares favourably to 1.23V for the hydrogen fuel cell. In practice, however, the theoretical cell potential is never approached due to the relatively poor oxidation kinetics of methanol and the problem of methanol cross over to the cathode. In comparison, hydrogen oxidation is very fast and consequently the performance of the hydrogen cell is better than that of the methanol cell.

Although the energy storage of neat methanol far exceeds the upper limit for rechargeable batteries (2509Wh/kg vs. 250Wh/kg for Li-Ion), methanol crossover in Nafion membranes limits the anolyte concentrations to approximately 0.5M (~41Wh/kg). This imposes severe practical limitations on the development of portable equipment. In order to increase the energy storage to an acceptable level, neat methanol (or highly concentrated solutions) will have to be stored and injected into a dilute feed solution. The control systems for such a system are unlikely to be readily adaptable to the sub-watt scale on volumetric grounds. Furthermore, water balance issues eliminate the practicality of air-breathing cathodes.

In order to maintain the correct water balance in a liquid feed system, water, permeating to the cathode by electro-osmosis, must be either recycled back to the anode or replenished from a secondary water tank. Carrying on-board water will decrease the energy density of the system and is impractical in this context. Recycling water requires a cathode flow-field, which would impose a significant parasitic load.

Toshiba has recently unveiled a technology demonstrator capable of delivering five to eight watts, enough to power a PDA[10]. The device is housed in a container roughly a third of a litre in size, weighing approximately half a kilo. Considering that the actual cell itself fills only 10cm^3 of this volume this proves to be a good example of the relative size and complexity of the ancillaries. Smart Fuel Cell, a German organisation, has recently announced a range of units fuelled by cartridges of neat methanol (storing ~120Wh) capable of providing 40W of electrical power[11]. Again the overall unit size is dominated by the need for water management and similar systems. Thanks in part to these high profile demonstrators methanol fuelled systems have received a significant amount of publicity.

2.2.3.1 Future Advances

As befits an emerging technology there is considerable continued development of the DMFC technology by a number of organisations[12]. In general, the focus of this research is to either improve the oxidation of methanol, by choice of catalyst or higher operating temperatures, or reduce methanol crossover.

Studies have indicated that Pt-Ru alloys are the most active binary catalysts for methanol oxidation, although additions of other materials (W, Mo, Sn, etc) can enhance this further. These materials are expensive and required in relatively high loadings (~1mg/cm^2) thus there is a need for further improvement. NEC, another Japanese developer, has reported successes from its use of carbon 'nanohorns' as electrode materials[13]. These materials can be used to produce an electrode with a large surface area and a microstructure that allows the easy diffusion of both liquids and gases. This structure also facilitates the creation of smaller platinum catalyst particles offering smaller loadings.

Alternative membranes have been investigated and positive results have been reported using composites or barrier layers. Similar improvements have been achieved with higher temperature (>140^{o}C) membranes such as phosphoric acid doped polybenzimidazole (PBI) which demonstrates a lower methanol permeability than Nafion.

Some researchers have moved in an entirely different direction for example the Israeli manufacturer Medis have patented an alcohol fuelled system that utilises technology more comparable to that used in Phosphoric Acid fuel cells[14]. Their use of a proprietary liquid electrolyte further simplifies the fuel cell design and thus it may be more applicable volumetrically to portable applications. They have quoted impressive energy densities claiming that values of 450Wh/kg will soon be achieved. Similarly they have estimated that units capable of powering a laptop computer will be available for 10-15$. It is difficult to accurately assess these claims as detailed technical information and performance data is not available.

2.2.3.2 Summary

While the energy available from methanol makes it a promising fuel the current solutions to the problems with crossover do not allow its full potential to be realised. As such DMFC are likely to be bulky units and not competitive with existing battery technology in the near term.

2.3 Nano-Technology And Microfluidic Devices

The typical series connected stack construction of fuel cell devices is not particularly suited to miniaturisation. Bulky compressive endplates and assorted gas and thermal management systems are less easily scalable and will dominate system size and weight at lower power levels. This leads to lower energy and power densities that are not competitive with existing power sources. Micro-scale power devices therefore require a re-evaluation and redesign of fuel cells. This is currently being addressed by nano-technological and micro-engineered solutions. This technology has grown rapidly within the last decade however it is still not commercially viable and the lack of a suitable fuel source at these levels has yet to be addressed.

Within the fuel cell arena the UK nano-technology community is lagging behind it's European and American competitors. At present the push for the miniaturisation of power systems is being spearheaded through US military funding[15].

A good example of commercial nano-technology is evidenced by the work at Motorola Labs, Lawrenceville, GA, who have developed a prototype of a ceramic-based microfluidic fuel delivery system for a miniature DMFC[16]. Previous DMFC systems have used discrete tubes to mix the methanol fuel with water and deliver it to the fuel cell. However, Motorola has successfully demonstrated the use of multi-layer ceramic technology for processing and delivering fuel and air to the fuel cell MEA. In the implementation, cells are arranged in a planar configuration and the completed ceramic DMFC assembly, excluding electronics, is 5cm by 10cm and less than 1cm thick and produces 100mW of electrical power.

2.4 Fuel Utilisation For Portable Power Applications

There are two routes that can be considered when the issue of fuelling is raised. One is the storage of pure hydrogen either physically as a gas or liquid, or chemically as a metal hydride, the other is the generation of hydrogen through the reforming of a hydrogen containing fuel. The former represents the ideal solution but has many practical problems including the lack of a hydrogen infrastructure. The latter is a more mature technology but typically operates on a larger scale and is not easily applicable to portable systems.

2.4.1 Hydrogen Storage

The hydrogen economy has been eagerly anticipated for several decades but thanks to low petroleum prices there have been limited market drivers. The increase in environmental awareness within the last few years has begun to drive development of more efficient and less polluting power sources. Hydrogen is seen by many as the fuel of the future since it is renewable and non-polluting. As such the storage of hydrogen has become increasingly important and has attracted significant research. The main methods of hydrogen storage can be divided into three categories: Pressurised fuel, liquid fuel, and solid fuel.

2.4.1.1 Pressurised Gas

Storage in a pressurised vessel is the established approach to hydrogen storage and many of the current prototypes and demonstrators rely on this option. However such pressure vessels are typically bulky and heavy due to the large quantities of thick steel plate used in their construction. This means that they have a very low energy density as only ~1% of their mass is hydrogen. Work on alternative materials has lead to the development of composites, such as carbon fibre wrapped vessels, which are lighter and stronger although more expensive. Using composite technology Thiokol, a US manufacturer, has developed a cylinder capable of storing 11wt% of hydrogen, equivalent to 2,046Wh/kg, at 5,000psig. While this holds great promise for vehicle applications the storage of smaller volumes becomes increasingly inefficient as the ratio of surface area to volume increases.

The adoption of cylinders of high-pressure hydrogen by the general public is hindered by the perceived danger of hydrogen and acceptance will require a massive re-education program. Similarly commercialising a high-pressure product would require an in-depth analysis of the safety issues probably leading to the incorporation of complex fail safe devices.

2.4.1.2 Liquid Storage

Liquid hydrogen may be stored cryogenically and has been considered for large-scale applications due to its high energy density, however, it would be difficult to adapt this storage method for portable applications.

2.4.1.3 Hydrocarbon Fuel Storage

Hydrocarbon fuels may be used indirectly as a store of hydrogen. In the case of PEM systems fuels such as gasoline or methanol require reformation to hydrogen (see later section). More recently thanks to the growth of SOFC and DMFC technology the direct use of these fuels has become more feasible and thus attractive. The storage of these fuels offers no real technical challenges but preventing accidental exposure during recharging demands further attention.

2.4.1.4 Rechargeable Metal Hydride

A more effective method of storage at low volumes is offered by reversible sorption. The most common storage medium is a metal hydride. Metal hydrides promise a low-pressure, compact, and moderately inexpensive storage system, and the technology for making and processing them is well developed. Sodium aluminium hydride is already manufactured at low cost by the tonne. The nickel-metal-hydride battery is a common energy source. Unfortunately, hydrides are either heavy in comparison to the hydrogen they carry or require high temperatures to release the stored hydrogen.

Primary challenges for researchers hoping to improve the hydrogen storage ability of these materials will be to improve their gravimetric capacity and achieve lower-temperature release of hydrogen. Leading the commercial end of the research field is the development of ever-smaller secondary metal hydride stores, such as those now available from HERA, of Nuremburg, Germany capable of operation (i.e. hydrogen release) at ambient temperatures[17]. Here, the development work has resulted in more convenient sizes of gas storage bottles becoming available for portable devices, though it has to be pointed out that this repackaging of the stored hydrogen directly reduces the stored fuel capacity. New types of secondary-hydride metal systems that are presently under development should offer further increases in the energy storage density of this type of system. Currently they are considered to be much safer than the high-pressure gas and are the storage medium of choice and have been incorporated into a number of prototype portable appliances.

These hydrides rely on a readily available source of hydrogen from which to recharge. It would be possible to recharge a hydride from a home electrolyser which could be made as user friendly as present home battery chargers. This would however result in a loss of over 50% of the input power compared to directly recharging a battery.

2.4.1.5 Primary Hydrides Systems

A number of compounds can be reacted with a chosen initiator (ie physical, chemical or thermal) to produce hydrogen. A common example would be the addition of an alkali metal to water. Devices of this type have been developed, a prime example being the "Powerball" sodium hydride system[18], but once the water store is factored into the size or weight of such a unit the overall energy density becomes uncompetitive with the other storage technologies.

An alternative more suitable to the limitations of portable power would be the catalytic decomposition of a liquid fuel. Millennium Cell are developing such a system, termed “Hydrogen on Demand”, for automobile applications and hope to create a fully commercial product in the near future[19]. This system uses the catalytic breakdown of an alkaline solution of sodium borohydride ($NaBH_4$) over a platinum catalyst to produce hydrogen. This system should be relatively simple, and with some clever engineering scale down to portable size since all it requires is a liquid inlet and catalyst.

The thermal method has not received the same level of interest, possibly due to the problems of controlling the input heat while preventing thermal runaway during operation. Thermal initiated devices are being developed through DARPA funding in the United States as well as by QinetiQ in the UK.

While they have an enormous capacity for hydrogen generation, these systems still have issues to be considered regarding the controlled rate of hydrogen discharge. Because of the large amounts of heat liberated during the chemical reactions that release hydrogen, further work is needed to make the system publicly acceptable for unattended operations and personal use. Manufacturability, cost and performance developments will follow on from these primary issues. NovArs GmbH is developing a portable PEMFC power generating device that features a fully integrated primary-hydride system for hydrogen fuelling. A number of the operating safety issues are addressed in this demonstration system by selective use of reaction catalysts and pressure-sensitive safety devices.

2.4.1.6 Future Technologies

Looking further ahead into the future, there may be breakthroughs in the development of gaseous hydrogen storage. The International Energy Agency currently runs the "Task-12"

Hydrogen Storage in Metal Hydrides and Carbon programme in order to improve both proven and concept materials' hydrogen storage capacities.

Carbon nano-technology (fibres, tubes, etc) has been the focus of much attention since the original reports of hydrogen storage values of 50%+ by weight[20]. Sadly these results have proved impossible to replicate fully although studies have highlighted how dependent the properties are on the preparation route[21]. Modelling of the expected sorption mechanism has suggested that 20% by weight may be the best achievable depending on the packing used.

2.4.2 Hydrocarbon Reforming

Given the problems associated with hydrogen storage many developers have investigated technique of hydrocarbon reforming. This mature technology has been successfully demonstrated for a range of fuels but problems of scale exist at the portable power level.

Most hydrocarbon fuels given sufficient heat, a suitable oxidant and catalyst can be converted into hydrogen gas and COx species. If these ratios are not optimised then at best the hydrogen yield will be reduced and at worst carbon will poison the catalyst or block the gas channels. In large systems the regeneration or recycling of the catalyst can mitigate this. In small systems it is difficult to control these ratios and the gas channels are much smaller.

Such devices offer the user the possibility of running their portable device on a wider range of intermediate fuels. For a reformer system to compete with compressed hydrogen gas stores, the chosen fuel would need to be widely available and of a high enough energy density to be accommodated within a similar system volume along with the reformer and control equipment. Though companies such as IdaTech Corp., InnovaTek Inc.[22] and Nuvera Fuel Cells Inc. are preparing reformers for commercialisation, these systems are far too large to be used in small, hand-held devices.

Primarily due to developments in nano-technology within the last few years significant progress has been reported in the miniaturisation of reformer systems. Results from Battelle[23,24] seem very promising as they have developed a micro-scale steam reformer, which although only $0.5mm^3$, can reform sufficient quantities of light hydrocarbons (butane, methanol) to produce hydrogen gas equivalent to 200mW of power. Miniaturisation will also rely heavily on the ability to optimise available fuel cell subsystem modules and interconnections when integrating them into one product[25].

2.5 Ancillary Fuel Cell Components

The available information on ancillary components within fuel cell systems is very scarce. This is primarily because many of the initial prototype units have been sold as bare stacks for demonstration purposes only, not as complete power supply systems. It is also possible that the developers do not wish to make the systems sound over-complicated to the consumer, and thus specifications regarding complete power supply products do not itemise the sub-systems components. Indeed, it is often impossible to tell which class of fuel cell is incorporated into many of the portable power supply products. Certain assumptions can however be drawn from consideration of the available technologies.

When attempting to package them into low-power, portable products the simplicity of an air-breathing, open-cell stack offers immediate advantages over forced-air, closed-cell stacks. For reasons of clarity it is helpful to make a clear distinction between the two characterising features of fuel cell devices that relate to how a device’s oxygen-supply and cooling requirements are met. Almost all fuel cell devices source their oxidant from ambient air and can, therefore, be referred to as “air-breathing”. Very few ancillaries are needed to operate this class of device, but a cathode directly exposed to air brings with it an increased chance of accidental contamination. The term “ambient air-breathing” is often used to distinguish low-pressure, open-cell stack devices from the more complex forced-air, or pressurised, closed-cell stack devices. In essence, to be truly ambient air-breathing, one side of each cell in a fuel cell stack must be open to the natural flow of ambient.

The ancillary devices required for operating an air breathing device are very limited; these stacks can be made to deliver electrical power simply by connecting a hydrogen supply and allowing the stack to maintain an appropriate operating temperature by the process of natural air convection over the stack. Forced-air stacks, on the other hand, are characterised by a closed-cell construction within which channels must be buried in order to convey the hydrogen and air/oxygen reactants to the active surfaces within each cell. This conveyance of fuel and oxidant must, necessarily, be effected with elevated gas pressure at the inlets to the stack. These stacks, therefore, require air compressors in order to function.

Unlike the open-cell stack systems, the closed-cell stacks take advantage of the fact that a more consistent power delivery can be achieved using the same number of cells if their hydration state is carefully controlled during operation. It is clear that a closed-cell construction is more appropriate for retaining control over the stack’s humidification levels, and makes possible the direct utilisation of product water. In order to maintain control over humidification levels within the stack, these fuel cells commonly feature more complex ancillary functions than the open-cell stack systems. In addition, as their rated power output increases, the need to internally control the stack operating temperature adds to the sub-system complexity.

Depending on the origin of the technology, the higher power output fuel cells (500W and beyond) are either adapted from open-cell stacks, requiring greater amounts of additional fan-assisted air-feeding and air-cooling, or are scaled-down closed-cell stacks that retain the water-balance management and cooling characteristics of their parent stack systems.

The majority of the applications for portable fuel cells are direct current, which eliminates the requirement for expensive power conditioning devices such as inverters or transformers. However, the voltage range of operation of a fuel cell stack will usually necessitate the incorporation of a dc-dc converter into the system to make it compatible with existing electronic devices.

3 POTENTIAL MARKETS

This section examines each of the potential markets available to portable fuel cell technology. Full details are tabulated in Appendix B.

Sub 100mW: It is difficult to envisage an application where current fuel cell technology could offer obvious advantages at this power level. This level of power is the domain of tiny devices that could run for many years off a normal battery. Recharging or the inconvenience of carrying replacements is not as great a driving force as it would be encountered in higher power systems. While it is not inconceivable that a micro fuel cell system could be developed, and indeed integrated chip based units are under consideration, these are still far from the market.

Other low power applications could include small sensors particularly for biological monitoring. Fuel cells as they currently stand, ignoring obvious specific drawbacks, are unlikely to be considered as potential replacements. Such applications require that the devices be sealed require little or no maintenance during its lifespan and that the unit is safe to the recipient.

100mW to 1W: This particular power bracket is perhaps the most difficult to consider. The power levels are suitable for a fuel cell to deliver and compact units would not prove difficult to integrate into the existing application. The main drawback is perhaps the lack of a suitable fuel supply.

1W to 500W: At these levels the fuel systems can offer increased performance, over the traditional battery or small combustion engines, however this is typically at the expense of size and weight.

3.1 Battery Replacement

Portable fuel cell systems have the potential to replace various types of battery over all of the defined power ranges. Taking a very general market view it is fairly easy to envisage the scale and value of the possible fuel cell market by looking at the current progress of the battery market itself. Within the battery market there is a natural development of technologies that has seen the gradual displacement of, e.g., Nickel-Cadmium (NiCd) batteries by Nickel-Metal-Hydride (NiMH) and Lithium-Ion (Li-ion). Essentially, certain fuel cell technologies will continue this technological progression, which has already begun with the introduction of “metal-air” fuel cells.

Table 2 contains information compiled from both *total* and *portable* battery sales. Also of note is that the markets for both rechargeable and non-rechargeable batteries are combined though it is useful to point out that non-rechargeable batteries account for approximately one third of the total. The portable battery market accounts for about 10% of total world-wide sales, and fuel cell technologies may be expected to penetrate some fraction of this market in coming years.

Of the specific markets noted in the table, Toys & Games (including audio equipment) and Lighting hold a surprisingly large share of the total market. From previous surveys of the intended applications of fuel cell devices, these two markets do not appear to be specifically catered for, although fuel cell-powered, hand-held flashlights have been used to demonstrate the compactness of fuel cell power sources. Apart from the challenging low cost of batteries used in toys, games and flashlights, fuel cells intended for these applications would have to be made sufficiently safe for use by children.

3.2 Portable Electronics Market

The portable electronics market encompasses high-tech, high-value goods applications such as mobile telephones, hand-held computers & notebooks, lap-top PCs, pagers, hand-held Geographic Positioning System receivers (GPS) & radios, monitoring sensing devices, cameras and video cameras. Currently, it is the NiCd battery that powers most of these types of devices world-wide, accounting for 70% of all battery sales in this market. Table 3 displays the world-wide sales information for batteries that are specifically intended for portable electronics applications:

Market information regarding three specific battery applications within the portable electronics market is given in the following sub-sections:

3.2.1 Mobile Telephones

Up to 1997, the three largest consumer markets for mobile telephones were in North America, Asia-Pacific and Europe, with the Asia-Pacific markets displaying the greatest increase in number of mobile phone users[26].

- There were just under 180million telephone subscribers in 1997.
- There were ~690million cellular phones in world-wide use in 2000.
- By 2002, it is predicted that the world will have 1,000million mobile phones.
- By 2003, it is predicted that the world will have 597million mobile phone subscribers.
- Predicted world-wide annual market growth rate is currently +11%.
- At this rate of growth the value of sales of mobile telephones will reach <$84billion.
- China is predicted to have the largest portable phone market by 2002

The preferred battery for these devices is likely to progress from NiMH through Li-ion to Lithium-polymer (Li-poly). At present, Li-ion battery technology offers the consumer a power source that can have at least a 1300mAh capacity, weighing ≈48g and offering a “talk-time” of 3-8hours and a recharge time of 4hours. Li-poly battery technology would be expected to better these specifications, and so too would replacement fuel cell technologies.

3.2.2 Portable Computers

No specific details of this market were available for this report, but the following observations have been published:

- Predicted world-wide sales of hand-held devices expected to increase: from 3.9million units in 1998…to 20million / 37million units in 2003[27].
- Estimated value of the market at 2003 is $7.6billion / 6.2billion[28].
- The Japanese market was responsible for 24% of all sales of portable PCs (4.7million units) in 1999.
- Latin American market, chiefly Mexico, shows strong growth.

It was reported by more than 80% of all notebook device users that battery operating time was insufficient and that the devices were heavier than desired. Consequently, replacement fuel cell technology would have to provide a device that could better the current battery technology in these respects. For example, a typical NiMH battery found in a laptop PC will have a weight of ≈1kg, an operating time of between 1.5 to 5hours and dimensions of ≈14cm×9cm×2cm. The energy capacity of the battery will be ≈36Wh, so this will mean that the "energy storage density" of the power source is ≈36Wh/kg. In comparison, development-stage fuel cell devices already achieve an energy density in the region of 240Wh/kg, indicating substantial capacity for meeting future consumer requirements.

3.2.3 Video Cameras

Sales figures for 1997 show a world-wide sale of at least 62million units, with a large proportion of sales occurring in Hong Kong, China and Japan. As for laptop PCs, the typical battery used in this type of device is NiMH or Li-ion, with energy capacities of ≈12Wh, and which may represent between 4% to 14% of the total cost of each unit.

3.3 Leisure & Outdoor Market

This market can cover a very wide ranging array of applications and consumer power requirements, but for this study it is taken to apply to "portable power products" for camping, sailing, workshops, outdoor lighting, toys & games and gardening equipment.

To some extent, a fuel cell based portable power supply represents a totally new market opportunity due to a gap in the existing portable power generator market. The reason for this is that for relatively low-power electrical demands (of up to 500W) the available power source technologies are limited to heavy and short-lived battery packs or noisy Internal Combustion Engine (ICE) generators. For this market, the possibility of generating electrical power from a silent and easily transportable power source is desirable. Being an early niche market, however, makes an assessment of the market value rather difficult at this time. The available information on electrical generators based upon Diesel, gasoline and gas fuelled ICEs only relates to units generating between about 1kW to 100kW of electrical power, and this market saw 385,000 unit sales in 1997, valued at $5,800million. An estimated 10% of this market has been proposed as becoming available to low-power, portable fuel cell based devices. Economic conditions appear to have a stronger influence over the growth of this market than others mentioned in this report.

Another application that has received much attention from fuel cell systems developers is powered gardening tools. Generally speaking, of the various powered tools, e.g., hedge-trimmers, grass-strimmers, rotavators, leaf-blowers, chain-saws and shredders, only lawnmowers are seen as being a profitable venture at this early stage. Furthermore, this only applies to the self-propelled, sit-on type of lawn mowers for which the power requirements are beyond the range covered by this report. However, it is worth pointing out that there is a valuable safety advantage associated with replacing a mains-operated, trailing-lead lawn mower for a cordless, fuel cell based version. Market information on powered garden tools is only significant for lawnmower sales, and was estimated to be in the region of $3billion in 1997.

3.4 Power Tools Market

Power tool power requirements cover at least two of the pre-defined power ranges referred to in this report; the lower power devices being those used around the home for DIY, and the more powerful tools used for professional workshop and construction site applications. Cordless, rechargeable-battery powered tools have rapidly replaced a major proportion of the mains-operated power tool market in which the lower power outputs of the cordless tools has not marred their “remote” operation advantages.

Table 4 indicates the current power tool market. NiCd domestic powered tools weigh in at around 1.4kg to 2kg, cost between $80 to $240 (in the UK) and have a capacity of ≈24Wh – requiring 30minutes to 5hours recharging times. Professional tools are considerably more expensive and understandably offer improved performance.

Planned fuel cell replacement power sources would most likely come in the form of an independent, belt-worn power pack that would plug in to power an array of hand-held tools. Although the tools would then regain a short length of cable, the operator will have gained a much lighter tool, capable of accessing more restricted working spaces.

3.5 Navigational Aids Market

This is a relatively small market, but due to the extreme emphasis on power source reliability it is possible that entry of fuel cell devices onto this market would be profitable. The portable and remote navigational aids of interest are powered buoys, which may require a faultless supply of power (≈10W) for up to a year at a time between maintenance operations. Though there may be between 20,000 to 40,000 of these navigational aids at present, the value of the power equipment market is worth less than $1million per annum.

3.6 Outside Broadcast Market

This is another of the small, but specialised, markets. Portable TV cameras that are used for transmitting outdoor news broadcasts can manage up to one hour of filming on a rechargeable NiCad battery pack, which stores ≈50Wh of energy and can cost over $240 per unit. As these batteries are usually built in to the camera, it would be desirable if the replacement fuel cell based device were lighter in addition to offering much longer (up to six hours continuous) operation times. The battery market value for this application is estimated at $10-$15million per annum.

3.7 Medical Applications Market

A small market that has the potential to grow enormously as the medical profession adopts more and more technologically innovative medical devices. Portability in medical devices can significantly help in the management of a limited number of expensive units, and also allows them to operate in the paramedic environment. Existing items of equipment that have portable capabilities include incubators, defibrillators, pulse oximeters and dialysis pumps. Some of these may see use outside of the traditional hospital environment, such as in outpatient's homes and in public buildings as part of their medical emergency livery.

Developments in this market have been recorded for the US only, but this indicated a market value of $11.9million in 1998 and was forecast to grow at a compound annual rate of 20% up to 2005. Challenges to the application of fuel cell devices in hospital environments may include ensuring that they remain easily cleaned and hygienic.

3.8 Education Market

It will become increasingly relevant and urgent for schools and colleges to introduce energy studies in the national curriculum in coming years – not least to support the need for fuel cell engineers in the near future. Though the market may represent an extremely worthy cause, it is unlikely to generate much profit.

The market for educational fuel cell demonstrators may be assessed by looking at the number of primary and secondary schools based in the more developed economic states. Including the European Union, Eastern Europe, the US, Australasia, Japan and China, there are ≈1.3million primary schools and ≈118thousand secondary schools existing as potential target markets.

Educational and demonstration fuel cells (primarily PEM) already exist for sale to educational establishments, but sales figures for these units have not been made available

4 APPLICABILITY OF FUEL CELL TECHNOLOGY

Appendix B lists potential markets that could be exploited by fuel cell and the general suitability of fuel cell technology to meeting the needs of the application.

4.1 Market Entry Issues

Reviewing the data the main issues affecting the penetration of fuel cells into the portable power market include size, weight and cost. Since the drive for most electronic devices is towards smaller and lighter units it is unlikely that the consumer will welcome an increase in either. The main issues relating to the size and weight are detailed below.

4.1.1 The Hydrogen Source and Storage Problem

The key technical issue that will delay the wide-scale introduction of fuel cell devices onto the portable power market relates to the hydrogen. The hydrogen source and storage issue is pervasive across the entire spectrum of hydrogen energy devices. At present, gaseous hydrogen obtained from compressed gas bottles or secondary metal-hydride stores remain the most accessible means of fuelling portable power generating devices, and the source of hydrogen is almost entirely derived from fossil fuels. Apart from the environmental issues it remains a fact that hydrogen is difficult to store in sufficient quantity, within small, lightweight and robust containers. Consequently, although numerous PEMFC devices exist for portable power applications, their portability or operational longevity can be severely compromised by the size and weight of the hydrogen storage and supply apparatus.

4.1.2 The Reformer Availability Problem

To some extent, the hydrogen issue may recede with the emergence of miniaturised fuel reformers. Though the overall system complexity increases with the addition of a reformer in a portable PEMFC device, it will allow a wider range of fuels to be used, and these may have fewer storage, transport and health & safety issues than hydrogen. Reformers that work on any of the sustainable bio-fuels (bio-ethanol, bio-Diesel, wood alcohol/methanol, vegetable oils and animal fats) would also have the advantage of producing near-zero net emissions of greenhouse gases. There is, however, the issue of the slow start-up time for reformers to consider. While a micro-engineered device might be capable of reaching operating temperatures significantly faster this will still result in an initial delay. Thus there is a requirement for an additional power source within the reformer system to initiate hydrogen production before the fuel cell power output becomes self-sustaining. The working temperature of these devices, and their exhaust gases also need special attention when designing the final, packaged product. This is especially important if the final product will operate in close proximity to the operating personnel, particularly if they are also mobile or in confined areas.

4.1.3 The Operational Lifetime Problem

Other than the fuel related issues, fuel cells devices, barring the tubular SOFC, face the challenge of having to demonstrate their long-term-operation capacity. This is mainly an issue of materials durability, once structures become exposed to the uncontrolled conditions of non-laboratory environments. Of major concern is the quality of air supplied, which, obviously, cannot be guaranteed under all operating circumstances beyond the laboratory environs. Studies on the effect of pollutants have shown that the catalytic activity in PEM devices is compromised in the presence of small concentrations of a range of hydrocarbon vapours, which may be encountered on an every-day basis.

4.1.4 The Water Balance Problem

Most of the PEMFC devices being used in portable low-level power generation applications are of the open-cell, or ambient pressure, type. These devices contain solid polymer electrolyte membranes that perform best under humidified conditions, i.e. when the fuel and oxidiser gases have been humidified before being fed into the fuel cell stack. The development of “next generation” fuel cells may aim to alleviate the need to control this water balance by using advanced membrane materials that maintain high proton conductivities under all operating conditions.

Fuel cells have been marketed as being "just around the corner" and "the next big thing" for many years but are only now beginning to appear in marketable form. This aggressive marketing over the last decades may cause problems especially considering the current scepticism for high technology ventures. Since the initial commercial units will receive considerable consumer attention the manufacturers are fully aware that there is no room for error and this may account for some of the reticence in approaching the market.

4.1.5 Cost

The consumer is unlikely to change or upgrade power sources unless significant improvements can be made to the existing system either in performance or cost. It is difficult to determine the relative costs of the competing systems since the technology is either designed (and costed) for larger applications (1kW+) or is still very much in development. The larger units are typically costed in terms of $/kW, which cannot be scaled to accurately reflect the costs of smaller units since the design considerations are completely different. In the case of the nano-technology solutions there are significant development costs to factor in.

5 KEY PLAYERS AND PROFILES

This section will highlight the organisations that presently have a prominent role in the advancement of portable fuel cell technology and highlight the key players. A full list is given in Appendix C.

5.1 UK Based

5.1.1 Polymer Electrolyte Membrane

5.1.1.1 Intelligent Energy Ltd.

Intelligent Energy is the UK's major PEMFC developer, with 40 employees, it has a 15000 square foot R&D and manufacturing facility in Loughborough and a head office in London. Its development activities presently include stacks up to the 25kW level, but it is also active in the production of small, low power stacks (1–100W) for portable applications. Whilst many expect PEMFCs to displace portable batteries, Intelligent Energy view rechargeable batteries and fuel cells to be complimentary technologies. Hybrid systems where either the workload is shared between the two devices or the fuel cell is used to maintain the battery charge have long been recognised as a sensible future power source, particularly in man-portable applications. Intelligent Energy has teamed with the specialist battery manufacturer Ultralife, who are a leading US/UK based producer of advanced lithium batteries. This alliance will see the combination of low power PEMFCs and rechargeable lithium-ion batteries to address a range of civilian and military markets.

5.1.1.2 QinetiQ

Established in July 2001, QinetiQ comprises the greater part of what was the UK Defence and Evaluation Research Agency (DERA). Active in research and consulting on many aspects related to energy generation and the environment, QinetiQ has worked extensively on alternative propulsion and portable power technologies. It has a wealth of experience in the design and application of portable proton exchange membrane (PEM) fuel cells operating on pure hydrogen or reformed fuel. It is presently leading research into the poisoning of fuel cells by airborne contaminates, which have a major impact on their future use. It is also involved in appraising existing hydrogen sources such as the characterisation of commercial metal hydride containers and in the development of novel hydrogen storage and generation systems. QinetiQ has combined fuel cells with hydrogen storage and battery technology to tailor power sources for specific applications.

5.1.1.3 Generics

Generics are an international organisation offering scientific and strategic consulting to a range of clients. Their experience in fuel cell technology has typically been employed to analyse market trends and competing technologies for investors or similarly interested parties. However they are presently developing a novel fuel cell design utilising mixed fuel/air feeds and selective electrode catalysis. They claim that their CMR (Compact Mixed-Reactants) approach, which can be adapted to all existing fuel cells, can quadruple stack power density and cut production costs by a third[29].

5.1.2 Solid Oxide

5.1.2.1 Imperial College of Science, Technology and Medicine / Ceres Power[30]

Imperial College are the primary UK developers of planar SOFC technology for portable applications. Through the Centre for Ion Conducting Membranes they have conducted research for many other UK companies. They have recently spun out their own planar technology forming, Ceres Power, a company dedicated to the further development of SOFC technology in the 1 - 10kW range. The intermediate temperature SOFC products being developed by Ceres are aimed at the fuel cell market by introducing new materials developments to improve its fuel cells.

The company is focused on tackling the smaller scale applications of SOFCs with its low-operating temperature systems, which use a special doped ceria electrolyte supported on stainless steel (for low cost and durability) and operates at just 500^{o}C.
They are, however, not immediately interested in the sub kilowatt market and have initially targeted automotive auxiliary power supply units (~5kW). Since these utilise both the electricity and heat generated by the SOFC it is perhaps the key market entry application for such systems. As an example, long distance lorries can spend half their time with the engines at idle to provide cab heating and power and this is estimated to cost $2.7 billion per annum in fuel and additional maintenance costs.

5.1.2.2 Birmingham University / Adelan

Adelan manufactures electrolytes and other ceramic parts for tubular SOFCs, drawing on technology developed at Keele and Birmingham Universities. They were founded in 1996 following the demonstration of a SOFC powered 3-wheeled vehicle with a 100W natural gas fuelled stack. They have since focused on successfully lowering the start up time to below one minute. They are developing SOFC products aimed at providing stationary, portable and mobile electric power in the 100W to 15kW markets. In August 2001 Adelan reached a funding agreement with TechSys Inc for the expansion of Adelan's laboratory facilities to advance technology development, product engineering and eventual production of SOFC products. At that time Adelan and TechSys said they expected to introduce their first production prototypes in 2002.

5.1.3 Direct Methanol

5.1.3.1 Newcastle University

Research at Newcastle University has contributed greatly to the development of the DMFC over the last decade with the majority of this work being carried out within research groups headed by Professor Keith Scott (Department of Chemical and Process Engineering) and Dr Paul Christensen (Department of Chemistry). Work carried out at Newcastle has furthered the fundamental understanding of reaction mechanisms in the DMFC, as well as improving the electrocatalysis of these reactions. In addition, MEA fabrication and engineering aspects of fuel cell operation and design have benefited from experimentation and modelling work peformed within these groups.

5.1.4 Fuel Processing

5.1.4.1 Johnson Matthey

Johnson Matthey is a speciality chemicals company and its principal interest in fuel cell technology is in catalyst and membrane development for PEM systems and the production of fuel processing technology, including hydrogen purification, for automotive and stationary applications. In April 2000, Johnson Matthey Fuel Cells was formed as a separate business unit. Their previous research programmes have resulted in a compact (~$350cm^3$), auto-thermal methanol reformer (Hotspot) capable of delivering $500W_e$ of hydrogen. Recently this technology has been successfully adapted for use with natural gas.

5.1.4.2 Wellman CJB

A division of Wellman Plc, Wellman CJB manufactures specialist oxygen and hydrogen gas generation and purification equipment. They have been developing fuel processors for automotive and stationary PEM systems for several years capable of generating hydrogen from light hydrocarbon fuel stocks such as methanol and ether.

5.1.4.3 Accentus

Accentus was launched in April 2001 by AEA technology as its new intellectual property business. They have inherited and subsequently developed over 1,000 patented ideas in a number of technology areas ranging from early concepts to commercial products. While they have recently gained attention for the development of Lithium-ion battery technology they are also interested in fuel reforming and associated storage technologies.

5.1.5 Nanotechnology

While there are a number of academic groups working in the UK on micro-engineered devices none are apparently researching fuel cell variants.

5.2 World-Wide

Appendix D identifies the key organisations outwith the UK that are involved, or are likely to become involved within the near future, in the research and development of fuel cell based portable power sources. Routes to production and the formation of suitable partnerships and alliances that will allow market access are as important a factor as the technological foundations when considering the likelihood of success.

In the consideration of PEM technology some of the more familiar fuel cell names have been omitted from the following overview because, although possessing technical competence at the portable level, it is not clear from available literature where their commercial ambitions lie for devices at the 500W level and below. Conversely as a result of the general lack of interest in portable power applications for SOFC systems the main developers are listed, regardless of scale.

5.2.1 Polymer Electrolyte Membrane

5.2.1.1 H-Power Corporation, USA

New Jersey based H-Power Corporation were founded in 1989 and claim to be the first company to sell PEMFCs commercially. Although they offer PEMFC stacks sized at several kilowatts for residential power generation, the development of portable units has always been one of their main priorities. They have a workforce of 150, and had a market capitalisation value of $0.4b in 2001 with revenues of $4m (2000), and they aim to be profitable by 2004. In July 2001 they opened a 90,000 square foot manufacturing and testing facility in Monroe, North Carolina.

With respect to the portable and mobile markets, H-Power believe that demand will be driven by consumer preference for smaller power sources with longer lives and lower weight, and that one of the earliest opportunities for low power fuel cells will be as battery substitutes.

They have been marketing portable and mobile units in the 35–500W range since 1998 under the trade name of PowerPEM. These units have been used for applications such as back-up power for mobile highway signs and industrial portable battery chargers.
In February 2002 H-Power introduced a pre-commercial version of its new E^{PAC}-500 fuel cell- based power source. The E^{PAC}-500 is a self-contained, rack-mountable 500W fuel cell power source, designed for outdoor or indoor use and intended, initially, for industrial customers. The unit is designed to run on compressed hydrogen.

The E^{PAC}-500 is being demonstrated in conjunction with H-Power's marketing partner, Energy Co-Opportunity Inc. (ECO), an association of more than 300 rural electric co-operatives serving more than 18million customers in 40 US states. A version of the E^{PAC}-500 has also been developed for the Japanese market, in partnership with Mitsui & Co.

In addition to ECO and Mitsui, H-Power have been pro-active in developing partnerships (portable applications and beyond). Other notable partners include Gaz de France, PSA Peugeot Citroen, Air products & Chemicals and Ball Aerospace.

5.2.1.2 DCH Technology Incorporated, USA

DCH sells fuel cells through its wholly owned subsidiary Enable™ Fuel Cell Corp. They are based in Valencia, California and have a workforce of 50 employees. They were market capitalised at $70m in 2001 with a $1m revenue in 2000.
They are currently marketing 10–30W passive PEMFCs for portable applications, with a total fuel cell product range of up to 10kW power delivery.

They licensed their first fuel cell from Los Alamos National Laboratories in 1997, and based on the patents of Wilson, they developed a passive 12Volt/12W air-breathing PEMFC. In conjunction with its joint venture partner, Daido Metal Ltd., DCH is targeting customers in the Japanese automotive, electronics and highway sign industries. The fuel cells are sold through NeWave, a 50/50 joint venture vehicle, and the first prototype units were sold in 2001. Daido anticipates a strong demand for the fuel cells and has invested approximately $1m in equipping a manufacturing facility to produce commercial volumes.

DCH announced in February 2002 that they had sold two 30W Enable™ fuel cells to the Pennsylvania Department of Environmental Protection to power remote logging stations. This follows the supply of similar units to the Texas Natural Resource Conservation Commission for a similar function.

5.2.1.3 Hydrogenics Corporation, USA

Hydrogenics designs and builds integrated proton exchange membrane (PEM) fuel cell systems for power generation as well as for fuel cell testing and diagnosis. Their product range includes fuel cell test stands, multi-kilowatt PEMFC stacks and a range of small PEMFC generators (HyTEF™ Series) in the range of 5–200W. Additionally, in February 2002, Hydrogenics demonstrated the HyPORT CTM power generator. This unit is capable of delivering 500W of power and is fuelled by hydrogen generated by a proprietary chemical hydride system. With this system, hydrogen is generated from sodium borohydride tablets dissolved in water and consumed as demanded by the fuel cell module. Notable business partnerships include General Motors, Nextel Communications and Toyota Tsusho Corporation (TTC).

5.2.2 Solid Oxide

5.2.2.1 Sulzer Hexis, Switzerland

In 1997 Sulzer Hexis was founded as an independent company. At that time, seven years of active research and development had already taken place. The company has special competence in the conception, development and production of high temperature fuel cells, particularly in the areas of materials development, process control and systems integration. At the end of the same year it started field testing its experimental units. The units were installed in Switzerland, Germany, Japan, the Netherlands and Spain and over 70 000 operating hours have been accumulated since 1998 (as of July 2001). With this experience, it has succeeded in developing a high-temperature fuel cell that covers the basic requirements for heat and electricity in a single-family home. The system is presently undergoing trials and will be introduced to the market as the pre-series system HXS 1000 Premiere.

5.2.2.2 Global Thermoelectric, Canada

Global Thermoelectric is a manufacturer of thermoelectric generators. In addition, it is now aiming to develop commercial SOFCs. At present it is focusing on residential, remote power and automotive auxiliary power applications, as well as small-scale industrial power generation. It aims to produce its first products in 2002, from a production facility built in 2001. Global Thermoelectric has alliances with Enbridge Inc, the largest Canadian gas utility, Suburban Propane, a US propane distributor, and Citizens Gas & Coke of Indianapolis.

5.2.2.3 Siemens Westinghouse, Germany/USA

Siemens Westinghouse was created in 1998 when Siemens acquired Westinghouse Power Generation (which had been working in SOFC for over thirty years, with several key pre-commercial units). Siemens Westinghouse Stationary Fuel Cells has its manufacturing headquarters in Pittsburgh, Pennsylvania. It specialises in power plant systems, including steam, gas, and hydroelectric generators. SW is leading the development of stationary tubular SOFC technology. It has successfully operated a 100kW co-generation SOFC in the Netherlands, and 250kW and 1MW systems are being developed.

5.2.3 Direct Methanol

5.2.3.1 Manhattan Scientifics Inc. / Novars

In the 1990s, Manhattan Scientifics Inc. became a publicly held company, providing capital for MicroFuel Cell and holographic data storage research and development. The company is developing its MicroFuel Cell Technology, a portable fuel cell system for small electronics, such as pagers and cellular phones[31].

The MicroFuel Cell is a working prototype and is at a point sufficiently mature to interest potential manufacturing partners. The fuel cell design was modelled on nature, with a collection and energy distribution scheme similar to capillaries and veins. The cell, which runs on a mixture of methanol and water, has achieved an energy output three times greater than the lithium ion batteries currently used for cellular telephones.

Manhattan Scientifics has acquired the intellectual property and commercial development rights to a mid-range fuel cell technology under development at NovArs Gessellschaft für Neue Technologien GmbH, Passau, Germany. The NovArs fuel cell effort has been directed toward high current, low voltage applications: lap-top computers, cordless appliances and power tools, wheelchairs, bicycles, boats and home energy fuel cell systems. Their fuel cell design is based on the conventional fuel cell stack with proprietary design differences that make it simpler, lighter, less expensive, and more efficient. Presently the NovArs fuel cell operates with hydrogen fuel.

Finally Manhattan Scientifics also is working to improve the safety of hydrogen fuel sources. As a working demonstration and proof of principle of its design, NovArs has developed the Hydrocycle, a prototype electric bicycle powered by a fuel cell stack that produces a power output of 170W. The development of the Hydrocycle prototype has commercial implications, both for its potential application in many other mid-size portable electronic applications, and for its more immediate application to the electric bicycle market. That market alone is estimated by Japan Cycle Press to grow to 3 billion bicycles and 1 billion electric-assisted bicycles before 2020.

5.2.3.2 Smart Fuel Cells, Germany

Founded in 2000, Smart Fuel Cells have developed prototypes of DMFCs aimed at the portable market, with units available specifically for video camera operation.

5.2.3.3 Medis Technologies, Israel

Medis was formed in 1992 as a commercial offshoot of Israel Aircraft Industries to exploit new technologies for the civilian market. Using its proprietary polymers, catalyst and electrolyte Medis is developing an advanced direct liquid methanol fuel cell that is not based around the standard polymer membrane. Their products are presently aimed at small-scale fuel cells primarily for portable electronics.

5.2.4 Microtechnology

5.2.4.1 Case Western Reserve University[32]

Researchers at Case Western Reserve have a prototype of a fuel cell with a volume of only 5mm^3. The research team has used microfabrication technology to print multiple layers of fuel cell components onto a substrate that will permit low-cost, high-volume production. Originally developed for the military so that the miniature fuel cells could be coupled with miniature sensors and a transmitter to send a signal to a remote receiver their potential in commercial devices, such as cell phones is even greater.

5.2.4.2 Fraunhofer Institute

Scientists at the Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, have developed a power supply for notebooks[33]. This fuel cell allows operation for up to 10 hours at a similar volume and weight as conventional batteries. The core of the new technology is a banded structure membrane fuel cell. With internal series connection for a flat, space-saving design. The fuel cell can occupy minimal volume and still provide the output voltage required for the portable computer. Hydrogen is supplied from a metal hydride. The technology is suitable for almost all battery-powered appliances. It is particularly interesting for portable applications such as camcorders, battery-powered tools, and mobile phones.

In the near future, researchers want to adapt the power supply to the dimensions and geometry of a notebook, in co-operation with various industrial partners. Researchers at the Fraunhofer Institute have also developed a high efficiency low-voltage DC/DC converter. This opens up new application possibilities for energy converters, such as fuel cells, thermoelectric converters, and solar cells.

5.2.5 Fuel Processing

5.2.5.1 PNNL/Battelle, USA

Pacific Northwestern National Laboratories and Battelle are at the centre of significant research effort directed towards the development of man-portable power sources predominately for the military market. They have focussed on the construction of micro-engineered devices (vaporisers, combustors, heat exchangers) combined with small catalytic reactors (primarily for steam reforming). They have demonstrated a number of small units capable of reforming light hydrocarbons such as methanol and butane and are hoping to test diesel fuelled systems soon. An example of the success of their miniaturisation is provided by a compact steam reformer unit capable of delivering $500mW_e$ of hydrogen with a volume of only $5mm^3$.

5.2.5.2 Lehigh University, USA

Engineers at Lehigh have conducted a detailed study of the design and construction of a silicon chip based methanol micro-reformer[34]. They micro-machined a prototype device from silicon containing channels with a cross section of 1mm by 0.23mm and a copper catalyst layer of only 33nm. External gas transport was handled through tubing directly attached to the chip. Graphite pads provided gas seals as well as a thermal conduit for heat between the chip and its externally heated stainless steel housing. The prototype also incorporates palladium-based micro-membranes for CO conversion and hydrogen gas separation. While this technology is still very much in the concept stage it is worth noting that micro-reaction engineering is a quickly maturing field.

6 REGARDING LEGISLATION AND FUTURE ENERGY POLICY

As a direct consequence of legislation concerning global warming there is a push towards reduced dependence on non-renewable energy sources. Hydrocarbon fuelled fuel cells are more fuel-efficient than current power generating technologies and produce less noxious emissions[35]. However they do still produce CO_2 and will be liable to carbon taxes.

6.1 UK Policy

To fulfil the demands of the Kyoto agreement the UK has stated that it is committed to a reduction in CO_2 emissions by 2010 of at least 20%[36]. The recent cabinet office energy review has indicated that this necessitates more reliance on renewable energy sources and a move away from hydrocarbon fuelled power stations[37]. However the UK has also strengthened its assertion that it will not make reductions if this results in UK industry becoming less competitive. When the recent actions of the US government concerning energy policy (withdrawal from Kyoto) and free trade (increasing number of import restrictions) are considered this suggests that the continuation of this policy cannot be guaranteed. The energy review also highlights the government's intention "to bring home the cost of carbon emissions to all energy users".

Hydrogen fuelled cells are non-polluting at point of use but the source of the hydrogen is unlikely to be as environmental friendly. Currently the majority of hydrogen is produced by the steam reforming of natural gas ($CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$) which is endothermic and a source of CO_2. It is hoped that in the future the hydrogen will be produced by the electrolysis of water by renewable energy. While this offers the ideal solution of a completely non-polluting cycle it is difficult to ignore that the energy produced from renewable sources could just as easily be fed into the grid and used for battery recharging. In fact since the production of hydrogen by electrolysis and its use in a fuel cell is half as efficient as charging a battery this would seem to be a more efficient use of the energy and would require little investment in a hydrogen infrastructure. Fortunately while this is true for portable systems it does not hold for transport and combined heating and power (CHP) applications which require a decentralised hydrogen infrastructure.

6.2 Environmental Issues

6.2.1 Scrap, Waste and Materials Recycling

On environmental grounds, the EC is pushing for stricter industrial waste reduction standards by setting targets for materials recovery, re-use and recycling. For example, directives that have been drafted for vehicles set the objective of re-using and recycling a minimum of 85% by weight of vehicle materials at the end of their service life by January 2015 (EC Directive 2000/53/EC Art.7). More responsibility will start to be placed on product suppliers to take used items back from the consumer for recycling in order to meet such requirements.

With regards to portable PEM and DMFC fuel cells, these are commonly found to contain the following materials: stainless steel, aluminium, titanium, carbon fibre reinforced sheets, graphite foils, rubber & silicone seals, speciality polymer membranes and catalyst-loaded membrane coatings. By mass and by volume, stainless steel and aluminium make up the vast majority of the materials inventory, and these represent materials already possessing well-established recycling infrastructures. On these grounds alone, it is estimated that many portable fuel cell designs can already offer 95% materials re-use/recyclability with ease. Of the remaining materials, the most likely to raise more than the usual level of concern regarding the environment are the polymer membrane and catalyst-loaded sheets.

Solid polymer electrolyte membranes are usually a composite construction of a fluorinated polymer matrix substrate sheet supporting a sulphur-compound bearing polymer electrolyte. Though there is the possibility of this composite releasing gaseous fluorine and sulphur compounds if incinerated, it is proposed that waste and scrap materials be dissolved in a suitable solvent and recast to make new membrane structures. Materials involved in the initial manufacture of these membrane sheets are proprietary knowledge of companies such as Gore and DuPont. Thus, it is difficult to obtain a clear understanding of the environmental issues in this case.

Owing to the value of the precious metals in the catalyst-loaded membrane coatings, it is highly likely that these waste and scrap materials will draw the attention of the original supplier or precious-metal recovery companies. A recent assessment of the life cycle costs of PEM stacks indicated that efficient catalyst recycling could reduce the environmental impact of platinum production by a factor of 20 - 100 times[38]. Maintaining a high recycling quota of portable devices will be problematic since the techniques used for larger systems, e.g. automotive, are not as easily applicable. The addition of a large refundable deposit to the initial purchase cost will make fuel cell systems less cost effective and deter customers from buying such devices. Similarly leasing the fuel cell is not immediately practicable for such small items.

Other than the above mentioned incineration issue, landfilled fuel cell materials should not pose any unusual environmental concern. For example, no ground water contamination should occur in the event of illegal dumping, as it has been demonstrated that water generated by the electrochemical reaction within the fuel cell is of a potable quality. Concern may only be raised over the possible materials used in the final, packaged power generator system, as this may contain further electronics and battery related materials which have a greater environment risk than fuel cell components.

The ceramic materials used in the standard SOFC are not inherently toxic but may produce potentially hazardous dust during decommissioning or destruction of the cell. The materials being considered for the next generation of cells contain greater levels of cobalt.

6.3 Health And Safety Issues

A well-designed fuel cell system should be no more dangerous to the consumer than a typical battery however there are more associated risks with such a system. Appendix E summarises the potential risks of an integrated fuel cell system. In general the main risks are associated with the fuel storage and the inexperience of the user.

6.3.1 International Standards

At present there are few standards regarding the installation and operation of fuel cell units whatever the application. As such there exists no acknowledged independent UK centre for fuel cell testing and evaluation. If fuel cells are to be adopted commercially this will have to change. An international committee has undertaken the development of an acceptable set of such standards (TC105) but as yet they are incomplete. The only fuel cell standard containing Health & Safety guidance that has been fully authorised, and is in general use, is the ANSI Z21.83. This was developed to cover stationary power systems fuelled by LPG or natural gas and is not yet applicable to systems fuelled directly by hydrogen. Therefore, ANSI Z21.83 is of little practical value for portable fuel cell systems, particularly while proven micro reformer technology is unavailable. Also the National Fire Protection Association (NFPA) 853 ”Installing Fuel Cells” document does not cover small (<50kW) portable systems.

Fuel cell standards aside, hydrogen safety alone is considered an obstacle to the implementation of fuel cell technologies. There are codes available on the safe storage and use of hydrogen (e.g. NFPA 50A and Code of Federal Regulations (CFR) 29 1910.103), but in the absence of published international standards for hydrogen use the onus is on manufacturers. The European Integrated Hydrogen Project (EIHP) and the International Standards Organisation (ISO) Technical Committee (TC) 197 is working on standards for hydrogen fuelled automotive applications, particularly for hydrogen storage tanks and refuelling connectors. Metal hydride storage does not appear to be covered by any of the working groups.

The International Electrotechnical Commission (IEC) is working on various aspects of fuel cell standards, through specialist working groups (WG). One of these, WG2, is developing a standard for fuel cell modules (i.e. the stack), and this standard will be applicable to all fuel cells irrespective of size or type. A proposal has been accepted to set up a working group (WG7) to draft a standard for portable fuel cell systems, and this will cover both safety and performance issues. Already within the European Community there are a number of existing directives that will apply to fuel cell systems as much as they do for any other commercial product, e.g.:

- The low voltage directive,
- The electromagnetic compatibility directive,
- The gas appliance directive,
- The potentially explosive atmospheres directive,
- The pressure equipment directive,

- The machinery directive.

It is very probable that a fuel cell system will fall within the scope of some of these directives. This introduces a significant additional challenge and expense to placing fuel cell systems onto the European market. For example, if the system is deemed to fall within the scope of the gas appliance directive it will need to be certified by a notified body, but it will have to be installed by an approved installer. Within the UK, only registered gas installers (CORGI) are permitted to install gas equipment.

Other health and safety issues that need to be considered are the Provision and Use of Work Equipment regulations, of particular importance for power tools, and the Manual Handling Operations regulations, which may restrict the weight of portable systems to below 20kg.

7 KEY RESEARCH AREAS

This section will identify the key areas of research that require addressing if each of the fuel cell technologies are to be more applicable to portable power systems.

7.1 Polymer Electrolyte Membrane

While the combined research of the last few decades has successfully solved the majority of the technical and scientific challenges associated with bringing PEM technology to the commercial market there still remain plenty of opportunities for improvement. The specific areas requiring address are listed below:

- Develop suitable anode electro-catalysts tolerant to carbon monoxide levels in excess of 100ppm, without increasing costs. This would allow the direct integration of the fuel cell with a simple reformer unit without the need for bulky gas clean up stages.
- Develop improved cathode electro-catalysts capable of reducing the over-potential encountered at open-circuit and enhancing the exchange current density. At present the greatest ohmic losses are encountered at the cathode and thus such improvements offer the greatest gains in efficiency or the reduction of the catalyst loadings.
- Develop a more cost-effective alternative to the current proton conducting membranes (perfluorosulfonic acid) without reducing performance. While some partially or non-fluorinated membranes have been developed (e.g. PEEK, PBSS) which demonstrate greater conductivity than Nafion their lifetimes are lower. This is because the lower dissociation energy of the C-H bond dominates the lifetimes of these hydrocarbon membranes.
- Develop proton conducting membranes not dependent upon humidification for operation at temperatures between 150 to 200^{o}C. At these temperatures the catalysts are not affected by the presence of CO and the reaction kinetics will be improved.

If these remaining challenges can be overcome then the potential for general commercialisation of PEM technology will be much improved. More specifically portable power applications demands that certain other issues are settled namely:

- The ability to operate at ambient temperature and pressure
- Using air as the cathode reactant
- Minimising irreversible heat losses to use air-cooling
- Developing efficient water management techniques

7.2 Solid Oxide

Tubular systems are unlikely to offer the properties desired by the portable power market however planar systems offer considerably more scope. While materials for the first generation of planar SOFCs have in large part been finalised, there are several research issues that need to be addressed in order to realise the highest possible performance at the lowest possible temperature. High performance leads to a reduction in the number of cells required for a given specification, thus reducing stack size and cost. Thus, lowering the overall cell (and consequently the stack) area specific resistance (ASR) has a direct effect on the eventual system cost. Improvements have been made to lower the cell ASR to as low a value as ~0.14 Wcm^2 at 800^oC. To reduce this further would require fundamental understanding of the underlying phenomena, which lead to substantial polarisation losses. The three polarisation losses are: (1) Ohmic – mainly in the electrolyte. (2) Activation or charge transfer – at both electrode (cathode and anode) – electrolyte interfaces. (3) Mass transfer of gases through both electrodes.

- Minimisation of the ohmic loss would require fundamental work on processing thin ceramic membranes and also some composition-microstructure work on the electrolyte.
- Minimisation of activation polarisation would require investigation of porous electrodes at the microstructure (or nano-structure) level, in addition to investigation of new compositions of the state-of-the-art materials, or altogether new materials.
- To minimise concentration polarisation, it would be necessary to investigate gas transport through porous bodies.

There is a clear need to lower the operating temperature so that inexpensive metallic materials can be used for the interconnects.

- Stacks based on anode-supported cells and operating at temperatures less than 800 °C should allow the use of ferritic stainless steels. Key requirement for such materials are that they should be well-matched in thermal expansion to the adjoining cell materials and have long-term corrosion-resistance in the stack operating environment.
- Optimisation of the composition of these ferritic stainless steels in conjunction with long-term corrosion studies is required.

Recent developments in SOFC technology have lead to the discovery of ceramic electrolytes that are capable of conducting protons at lower temperatures (200-500^oC). If these materials can be successfully incorporated into a fuel cell then it could be more suitable for portable applications. In general, if SOFCs are to be seriously considered for portable power applications there is a need for demonstration units to be made available.

7.3 Direct Methanol

Many of the recommendations that apply to the PEMFC technology also apply here but there are several specific areas that require addressing.

- Development of low-cost membranes that exhibit lower rates of methanol crossover. This would eliminate the need for a dilution system, with the resultant savings in volume and weight. Such membranes should also allow thinner and therefore less resistive membranes to be used.
- Similar reductions in complexity can be achieved for the demands of water balance if membranes with lower rates of water permeation are investigated.

- Further catalyst development is required to improve the rate of methanol oxidation. Ideally such materials should be less expensive and be required in lower catalyst loadings than at present.
- Alternative membranes that can support continued operation at high temperatures thus enhancing the methanol oxidation should be examined.

7.4 Nanotechnology

The review of the potential markets has shown that the present fuel cell technology is generally too bulky and heavy to be an effective replacement for battery powered systems. This therefore necessitates the miniaturisation of key fuel cell systems, especially reformers.

There is a limit to how much improvement can be obtained from using lighter materials or space saving designs thus nano-technology or micro engineering must be employed. Solutions based upon such technology must follow established processing paths, as the development of novel, fuel cell specific techniques is likely to be expensive, making such devices less cost effective. Therefore the development of these is likely to proceed by the following path.

Selection of construction materials / processing route
- micro-machining of steel
- etching of silicon
- screen printing/casting of membranes

Coating channels with suitable catalytic materials
- fuel reforming (steam/POX)
- hydrogen stream clean up
- exhaust gas combustion
- fuel combustion for start up

Integration of whole system

One potential drawback to this technology is that at present the devices tested have been single cell or low power (<100mW) and scaling up to higher powers may have associated problems analogous to that of scaling up to a stack.

7.5 Hydrogen Supply

Current methods of hydrogen storage are still too heavy or bulky to be widely applicable for small-scale man-portable fuel cell devices. In fact this is one of the greatest challenges needing to be overcome to make man-portable fuel cells viable. Despite being very difficult to store hydrogen has a very high energy content and even one percent hydrogen by weight is equivalent to 266Ah/kg. A number of methods of hydrogen storage or generation have potential but need further improvements to become viable. These include: -

- *Carbon nanofibres/nanotubes:* The high capacities of carbon nanoadsorbants such as nanotubes and nanofibres need to be verified before these materials can be considered as suitable hydrogen storage media. Sufficient adsorption at room temperature would need to be demonstrated. Additionally the weight of the entire system, which might consist of a pressure container and pressure-reducing valve, would need to be minimised.

- *Hydrolysis:* The hydrolysis of primary hydrides such as lithium hydride and sodium borohydride has the potential to produce large quantities of hydrogen from a low weight system. However these systems suffer from difficulties controlling the reactions and providing high rates of hydrogen generation. The control problem is in part being addressed by using alkali-stabilised solutions with decomposition being achieved catalytically. To become viable the control system would need to be further refined and the weight reduced.

- *Thermal decomposition:* Groups in the UK and US are investigating methods of hydrogen generation by thermal decomposition of hydrogen containing compounds. These offer lightweight systems. However, some issues still remain to be solved before the systems become viable. These include the heat management of the reactants and optimisation of the ignition and control systems.

- *Metal hydrides:* Metal hydrides are a proven technology, which are capable of storing large quantities of hydrogen in a low volume system. For man-portable applications these materials will be required to operate at ambient temperatures. However, current ambient temperature alloys typically store only 1.5 to 2 % hydrogen by weight. Since this is an established technology it is likely that only small improvements in capacity are possible. It is likely that these improvements will come from reducing the operating temperature of lighter alloys such as alloys of lithium and magnesium.

- *Compressed gas storage:* The development of composite cylinders for vehicles is improving rapidly with capacities of 7.5 % achieved and 11 % demonstrated in a prototype cylinder. Cylinder storage becomes much less efficient as the size of the system reduces and it highly unlikely that a cylinder capable of fitting in a laptop or mobile phone would have significant capacity. However, for medium scale applications such as power tools compressed gas storage might become applicable but this would need further investigation. Lightweight pressure regulators would need to be developed. The major issue is one of safety, since high-pressure (300 bar) gas in a consumer electronic device would raise many issues.

7.6 General Recommendations

Whilst there exists a number of consumers willing to adopt new technologies purely on the basis of novelty most future purchasers of fuel cell powered products will require that the benefits are obvious and well demonstrated. The small number of current demonstrators means that hard data will take some time to become widely available.

8 UK SWOT ANALYSIS

This section contains a critical assessment of the current status of the UK with regards to its readiness to exploit the emerging market for portable fuel cells. It follows the format of a SWOT analysis in that the Strengths, Weaknesses, Opportunities and Threats will be presented.

8.1 Strengths

8.1.1 Good Academic Network

UK academic institutions have a strong tradition of interdisciplinary research and have constantly shown themselves to be keen to work with industry and flexible in their research goals.

8.1.2 Green Technology Supported

The present UK Government has indicated its desire to support ‘green’ technologies or more specifically those with a minimal carbon impact. To fulfil the reduction in CO_2 emissions of at least 20% by 2010 demanded by the Kyoto will necessitate more reliance on renewable energy sources and a move away from hydrocarbon fuelled power sources[36]. This policy has led to the formation of a number of new prospective strategies, a good example of which is given by the draft of "Powering Future Vehicles" which seeks to provide a framework to support a shift to low-carbon vehicles and fuels[39]. Further support for these cleaner technologies is provided by the European Commission through such programmes as the "Clean Urban Transport for Europe" demonstration project[40]. This project has been awarded 18.5 million, one of the largest amounts ever given, to construct and operate a fuel cell bus in nine European cities.

8.1.3 Existing technology seen as polluting

The existing power technologies are generally sources of pollution, either as a product of operation, such as engines or during disposal such as batteries.

8.1.4 No Preconceived Public Opinion About Fuel Cell Technology

The general public has not been significantly exposed to fuel cell technology and is unlikely to hold any specific prejudices against adopting it. However initial market entry systems will probably have to rely on "early-adopters".

8.1.5 Faster Recharge

Battery charging is comparatively a much slower process to simply refilling a fuel container with a liquid or gas, thus fuel cell devices will always offer users greater daily runtimes.

8.2 Weaknesses

8.2.1 Few Developers, One Organisation Deep In Places

Within the UK some aspects of fuel cell research and development are under-subscribed, particularly nano-technology, and further advancement within these areas is heavily dependent on a small number of organisations. This is of particular concern for larger organisations for whom fuel cells are not their main area of interest.

8.2.2 Limited dedicated manufacturing base

At present there is no mass-production facility within the UK geared towards the production of fuel cells. Some organisations are in the process of developing such capabilities however initial market penetration will require significant investment and early units will be expensive.

8.2.3 No hydrogen infrastructure

There is no hydrogen supply network and it would not be a simple task to convert the existing fuel infrastructure to suit. The DMFC is more fortunate in that it would be considerably easier to convert the existing infrastructure because fewer alterations would be required to distribute another liquid fuel.

8.2.4 National electricity grid

The UK is already served by a reliable network of electricity generators covering the majority of the population. It is difficult for fuel cells to compete directly with this existing electricity supply and as such there are few drivers for the application of fuel cell technology[41]. This has particular impact on the application of fuel cells to domestic power and heating usage and but also ensures that very few users of portable electrical appliances will be unable to gain access to overnight charging.

8.2.5 Public perception of hydrogen/science in general

Thanks to past misunderstanding the danger of hydrogen has been over-emphasised and the public are unlikely to accept it as a future fuel without misgivings. Recent high-profile issues have further tarnished the public’s acceptance of safety assurance from scientific experts.

8.2.6 Long build up

Fuel cell technology has been presented as the "next big thing" for some time, some potential investors may feel that this is too long term an investment. Continued hyping of the technology in the mainstream press and other literature will lead to apathy if the claims aren't eventually met.

8.2.7 No obvious route to market

There is no obvious niche market for portable fuel cells offering "a foot in the door" for the technology. Fuel cells are initially aiming to replace established technologies, mainly batteries, which is always a difficult process. For these applications fuel cells do not enable a new capability but rather an improvement in performance. Unless sizeable improvements, a factor of ten is routinely quoted in marketing literature, can be demonstrated then consumers are unlikely to change from their existing system.

8.2.8 Lack of technology demonstrators

Compared to other European countries and the US, the UK has little in the way of public demonstrators. The demonstrators that are planned tend to be using less favoured technology such as phosphoric acid (Woking Council[42]) and alkaline (Islay[43]) fuel cells.

8.3 Opportunities

8.3.1 Push for renewable/non-polluting energy supplies

Hydrogen (or a regenerable chemical storage medium such as borohydride) offers a completely non-polluting fuel source. While engines and microturbines can be adapted to operate on hydrogen and therefore compete with fuel cells for higher power applications difficulties in scaling them down mean that fuel cells have little competition, other than batteries, in the portable market.

8.3.2 Future advances in battery technology appear limited

At present it is difficult to see where the next advances in battery technology will come from. The electrochemistry appears to offer very little opportunity for obvious improvement and where it does leads to more environmental unfriendly chemicals. Improvements in the control of electrode microstructure may offer significant improvement but this is a long-term consideration.

8.3.3 EC regulations on waste electrical goods

The UK ratification of the EC regulations relating to waste electrical goods[44] will strongly enforce the need to recycle. Since this will effect all manufactured goods equally, the economic necessity for recycling of fuel cell devices may not be as much as a drawback as feared.

8.3.4 Adoption of Fuel Cell Technology in other markets

The application of fuel cells in higher profile transport and CHP applications will require that certain issues, many of which have a significant overlap with portable power (fuelling infrastructure, recycling, manufacturing, etc), be addressed.

8.3.5 Fuel Cells Are A Young Industry

Fuel cells are an emerging technology and there is still time to become involved at an early stage.

8.4 Threats

8.4.1 Currently no economically viable renewable hydrogen source

It has been estimated that the global production of hydrogen would only supply the UK with 60% of its energy requirements[45]. While this figure is unnecessarily gloomy, since production will increase to meet the future demand, it does raise an important point.

Hydrogen can be produced by the electrolysis of water or through the reforming of natural gas. The electrolysis of water is more favoured as it is completely non-polluting, depending on the source of electricity. Unfortunately it does not seem economically sound to produce hydrogen with a 10-30% loss, (more including transportation losses if necessary) just to convert it back to electricity with a further 50% loss. In comparison direct transmission of the same electricity across the UK national grid would only lose 5-10%. However as the energy demands of portable power applications are likely to remain low in comparison to heating, lighting or transport requirements these losses may be acceptable. Since current renewable energy sources only account for a small fraction (~1%) of the UK energy demand it would take a sizeable investment to approach the level required to meet the full demand.

Without a renewable source capable of generating sufficient quantities of hydrogen this technology seems less competitive. This is however being addressed through continued support of these technologies by the DTI's Sustainable Energy Programme[46]. Examples of such future sources include the production of methanol from the gasification of biomass. This offers a possible renewable fuel source as well as the potential for a good degree of self-sufficiency (projected to meet ~90% transport demand[47]) and this methanol can be used in a DMFC or stored and reformed when required to fuel a PEM system.

It is important to note that the development of an UK hydrogen infrastructure cannot be undertaken in isolation of the rest of Europe. If this were to occur it would lead to the formation of a logistical barrier between the hydrogen economy and the petroleum economy.

8.4.2 Competition breeds secrecy

As market ready systems near completion developers are understandably reticent to reveal information about their research areas.

9 RECOMMENDATIONS

This section aims to provide recommendations, based on the preceeding analysis, relating to UK activities within fuel cell research and development. Acting upon these recommendations will enhance the UK's commercial prospects and competitiveness in portable power markets.

9.1 Combined fuel cell/micro-technology research

Nano-fuel cell technology is presently being all but ignored within the UK. This technology if successful offers specific benefits for portable markets particularly with regards to the reduction of size and weight. Equally if mass-production techniques used in silicon chip production can be adapted to nano-fuel cell construction then this could offer much needed cost reduction.

Towards these ends facilitating a discussion between the manufacturers of electrical goods and fuel cell companies and encouraging them to pool resources would offer the most obvious short-term benefit.

9.2 Hydrogen storage research

The storage of hydrogen is of particular importance to transport applications and has attracted a large amount of interest. One major programme that is addressing this area is exemplified by the International Energy Agency's Task 12 hydrogen storage project[48]. This aims to identify metal hydrides or carbon materials that are capable of 5 wt% hydrogen capacity with a desorption temperature of less than 100°C. This is the necessary target for economic onboard hydrogen storage for vehicles. So far, 14 metal hydride and two carbon projects have been completed or are currently under way to evaluate formulation and processing techniques for optimising hydrogen storage.

The potential for high-density hydrogen storage in carbon structures (nanotubes, monofilaments, etc) has been the subject of much research yet no consensus has been reached. While this work has resulted in some useful developments in other technology areas a concerted effort to finally answer the carbon storage question would be of great benefit.

9.3 Public education/demonstrator campaign

The number of fuel cell demonstrators currently underway in the UK pales beside the other fuel cell developing nations. This obvious development gap needs to be addressed so that the benefits of fuel cell technology can be demonstrated. These benefits are vividly indicated by the major UK fuel cell demonstration project by Woking Borough Council[42]. Their overall energy efficiency initiative has lead to investments of £2.5 million over ten years with savings of over £4.7 million. Thus such examples as well as demonstrating environmental benefits can highlight the economic rewards.

Existing demonstrators can be divided into either stationary or transportation applications. The present level of development of UK technology is not aimed at the typical combined heating and power applications and any demonstration in this power range would currently require a fuel cell system to be imported. The transportation range offers more potential but the lack of a mass market UK car manufacturer and hydrogen store offers further complication.

A better option may be the incorporation of fuel cells into the educational curriculum. With suitable subsidy or sponsorship small fuel cells could be made available to schools. As well as exhibiting the technology this might provide a small niche market and encourage diversification of fuel cell manufacture.

Another benefit of such programs would be challenging the misconceptions regarding the safety of hydrogen fuel. A good example of positive press for hydrogen safety is given by the BMW 7 series[49]. This combination of a hydrogen-fuelled internal combustion engine and a SOFC auxiliary power unit has been rigorously road tested. The fleet of fifteen vehicles has reached a combined total of 100,000 miles driven during which three cars have suffered crashes with no deleterious effects.

Any future demonstrator will provide vital operational data and highlight potential problems that may have been overlooked. This information will be vital for the generation and future implementation of standards for fuel cell devices.

9.4 Fundamental fuel cell research

As detailed in a previous section there are still a number of fundamental areas of research that require further attention. Some of these are being well addressed through EPSRC/DTI[50] funding however it is difficult to guide research and some areas are falling behind.

A problem seems to occur in the transfer of this technology from academia to industry[51]. It is difficult to determine whether this is due to a perceived reticence of UK industry to take on new ideas, leaving researchers to spin the technology out for themselves or rather the researchers wishing to personally gain the full benefit of their research.

The technology review highlights the fact that only one system offers the potential to meet the needs of portable power in the short term. Thus it seems sensible to concentrate any future resources allocated to portable power onto research on PEM fuel cells. Due to the similarities between PEM and DMFC any success in one area should feed relatively easily into the other.

9.5 Hydrogen infrastructure

In the absence of an existing hydrogen infrastructure the route to future hydrogen usage in portable equipment has to be considered. Simply waiting to take advantage of any future infrastructure developed by the transportation market drivers offers no real benefit as such a system may be incompatible with the demands of portable devices.

An interim route may be offered through the use of electrolysers either as home units or centralised recharging points. This first requires a technical and economic analysis of the feasibility of these home/distributed electrolyser units. If the results from these studies prove favourable then a demonstration of the integrated technology would be the logical next step.

Examples of such an approach are given by the European Commission funded[52] Urban Solar Hydrogen Economy Realisation (USHER) project[53], which is examining the centralised production of hydrogen from a solar powered electrolyser to fuel a fuel cell powered bus. In a similar manner the Scottish Fuel Cell Consortium[54] have announced plans to link a hydrogen infrastructure to the 500kW LIMPET wave power generator[55] on the island of Islay.

10 TABLES

<table>
<tr><th>Power Range</th><th colspan="5">Market Name and Scope of Power Ranges Covered</th></tr>
<tr><td><0.1W – 1.0W</td><td rowspan="4">Battery Replacement Market</td><td rowspan="3">Portable Electronics Market</td><td rowspan="2"></td><td></td><td>Education Market</td></tr>
<tr><td>>1.0W – 10W</td><td>Navigational Aids Market</td><td rowspan="3">Medical Applications Market</td></tr>
<tr><td>>10W – 100W</td><td rowspan="2">Power Tools Market</td><td rowspan="2">Outside-Broadcast Market</td></tr>
<tr><td>>100W – 500W</td><td>Leisure & Outdoor Market</td></tr>
</table>

Table 1 - Comparison of Power Ranges and Potential Markets

Financial Year	Market Value at 1997 Prices ($-billion)	Predicted Annual Growth	Ranked Largest Market Sectors	Ranked Fastest Growing Market Sectors
1997	33.2[56] / 32-34.5[57]		1.Games & Toys	1.Electronics
1998	35.6[56]		2.Lighting	2.Communications
1999	2.6[26] / 36.2-47.2[58]		3.Tools	2.Medical
2000	39.2[56]	+6% to 2000[56]	4.Communications	3.Tools
2001	6[59]		5.Medical	4.Toys & Games
2006	4.2[26]	≈+15% by 2010[26]	6.Electronics	4.Lighting

Table 2 - Battery Markets

<table>
<tr><th>Financial Year</th><th>Market Value at 1997 Prices ($-billion)</th><th>Predicted Annual Growth</th><th>Ranked Largest Battery Technology Market</th><th>Ranked Largest Consumer</th></tr>
<tr><td>1997</td><td>3</td><td rowspan="4">+12% / +40%[60]</td><td rowspan="4">1.NiCad (30-35Wh/kg)
2.NiMH (45-60Wh/kg)
3.Li-ion (120-150Wh/kg)</td><td rowspan="4">1.United States
2.Europe</td></tr>
<tr><td>1999</td><td>>7.54</td></tr>
<tr><td>2001</td><td>>10</td></tr>
<tr><td>2003 (forecast)</td><td>6</td></tr>
</table>

Table 3 - Batteries for portable power markets

<table>
<tr><th>Financial Year</th><th>Units Sold (million)</th><th>Market Value Prices ($-million)</th><th>Sustained Annual Growth</th><th>Ranked Largest Consumers in 1998</th></tr>
<tr><td>1975</td><td>-</td><td>-</td><td rowspan="3">+4%</td><td rowspan="3">1.Europe
2.North America
3.Asia
4.Latin America
5.Australia
6.Africa</td></tr>
<tr><td>1996</td><td>89</td><td>5,870</td></tr>
<tr><td>1998</td><td>89</td><td>6,400</td></tr>
</table>

Table 4 - Power tool market

A APPENDIX A - FUEL CELL SYSTEMS

ORGANISATION	PRODUCT & APPLICATION	SPECIFICATION (ascending order of min. power output)	HYDROGEN SOURCE	FUEL CELL SYSTEM ANCILLARIES	ADDITIONAL INFORMATION
Current Status of Fuel Cell Technology: ***COMMERCIAL PEMFC PRODUCTS "AVAILABLE".***					
Ball Aerospace & Technology Corp. USA. (Product manufacturer)	PPS-50: Portable power supply for e.g. radio comms. PPS-100: Portable power supply for e.g. radio comms.	**50W** / 12Volt Dimensions (cm)≈11×20×20 Weight=2.9kg Fuel: gH_2, Oxidiser: forced air 1-minute start-up time $T_{operating}$=-20°C to +50°C @ 0-95%RH **100W** / 24Volt Dimensions (cm)≈11×20×25 Weight=3.8kg Fuel: gH_2, Oxidiser: forced air 1-minute start-up time $T_{operating}$=-20°C to +50°C @ 0-95%RH	2×metal-hydride gas bottles, storing ≈1kWh energy per bottle. 1×compressed gas bottle, storing ≈700kWh energy. In development: Lithium-Aluminium-Hydride/Anhydrous Ammonia reactor to produce self-regulated supply of low-pressure gH_2 (6%wt, 800Wh/kg)	Self-contained ancillaries: -LCD display -Forced-air fan -Power controller	www.ball.com/aerospace Stacks to be supplied by H-Power through a memorandum of understanding. Products field-tested in military trials – see entry for DARPA.
Ballard Power Systems Inc. Vancouver, BC, Canada. (Stack and product manufacturer)	Portable power supply:	**≈250W** power supply unit	-	www.ballard.com Units sold to **The Coleman Company Inc.**; for outdoor camping products, and **Matsushita/Panasonic/National/NAiS**; most likely for powering portable entertainment devices.	

BCS Technology (Stack manufacturer) *BCSTech stacks and further packaged products are also supplied through:* Fuel Cell Resources Inc.	Natural Convection Cells: Bare, open cell stacks.	4-24 cells: **3W**-150W 2.4-15VoltDC / 1.3-10Amp Cell active area=10, 25 or 50cm^2 $T_{operating}<+70$ or +75°C	None specified, but stacks can operate on reformed fuels in which the CO content is in the range of 10-25ppm.	All stack units are "self-humidifying". Control boxes for stack units up to 500W are available as additional items.	www2.txcyber.com/~bcstech/ Related site: www.fuelcell-resources.com Fuel Cell Resources, Inc. is currently investigating the establishment of a joint venture to provide capital for further development and commercialization of its membrane technologies and for mass production of its fuel cell products.
	Forced Convection Cells: Bare, closed cell stacks.	10-32 cells: **150-500W** / 6-20VoltDC / 25Amp Cell active area=64cm^2 $T_{operating}<+70$ or +75°C			
ElectroChem Inc. MA, USA. (Stack and product manufacturer)	EC-PDU: Portable Demo Unit	**45W** / 12V(DC) Dimensions (cm)=50×42×18 Immediate start-up capability	-	-Power conditioning unit. -Demo case including CD player with speakers.	www.fuelcell.com Products are not freely available for commercial sale at this time, only to other research organisations and education establishments.
	FC50-O3SP: Bare stack assembly for laboratory test and demonstration	**50W** (100W peak with cooling) 7-cells, each 50cm^2 active area Dimensions (cm)=15×15×15 Weight=4kg $T_{operating}$ <100 C	Suggested operation on 99% purity bottled gH_2 and gO_2 at 3atmos.	None supplied, but fan-assisted cooling recommended at higher power output rating.	
	EC-Powerpak-200: Portable test and demonstration unit.	**200W** (400W peak) / 12Volt(AC/DC) / 16Amp 17-cell stack Dimensions (cm)=23×23×41 Weight=9.1kg 40-50% efficiency	50psig gH_2 & gO_2 supplies required (bottled gases not supplied).	-Forced-air fan-cooled unit. -Water management system (waste water ejector).	

	FC200-O1SP: Bare stack assembly for laboratory test and demonstration	**200W** (400W peak) 17-cells, each 50cm^2 active area Dimensions (cm)=15×15×25 Weight=8kg $T_{operating} < 100$ C	-	Fan assisted cooling recommended, and "special cooling" recommended at higher power output rating.	
Electro-Chem-Technic Oxford, U.K. (Stack and product manufacturer)	FC03 PEM Fuel Cell System: 2-cell stack for remote power applications – radio, CD/cassette player, LED displays, toys.	**1.2W** / 5V(from DC-DC converter) Dimensions (cm)=6×6×3 Weight=200g	gH_2 supplied from: Sodium-tetra-boro-hydrate salt ($NaBH_4$) solution (in contact with Pt catalyst on fuel cell electrodes 20li Metal-hydride store (≈10cm length bottle) 1li Ambient-pressure gas bag (17cm×20cm)	Stack is integrated onto circuit board containing: -DC/DC converter, -H_2 gas line connectors and purge valve, -electrical output connectors. gH_2 sources supplied separately.	www.ectechnic.co.uk PRODUCT WITHDRAWN until supplies of Membrane Electrode Assemblies (MEAs) have been re-established (late 2002)
Element 1 Power Systems Inc. CA, USA. (Product manufacturer)	Small demonstration & portable power stack kits:	**1W** stack starter kit $84.95-$124.95(high power stack option) **3W** stack / 1.5Volt / 1-2Amp $300-$500 **6W** stack / 3Volt / 1-2Amp $520-$900 **10W** stack / 5Volt / 1-2Amp $700-$1300 High power stacks also available for 25-2000Ws output	gH_2 sources can be ordered as part of each fuel cell demo kit. Sources include PEM-electrolyser units, Alkaline electrolysis units or bottled gas. Stack back-pressure is raised by bubbling exhaust gH_2 through two test tubes filled with water.	Forced-air cooling fans can be ordered separately for continuous power operation of stacks. Electrolysers, gas scrubbers and solar panels also available for complete demo kits.	e1ps.tripod.com/E1PSWebsite

H-Power Corp. USA. (Stack and product manufacturer)	PowerPEM-D35: For demonstrating the portability of a fuel cell power supply system	**35W** / 12VoltDC	ST1-MH (metal-hydride) Hydrogen supply bottle sold separately	Self-contained ancillaries: -Cooling fan -Forced-air pump -Power controller -Start-up battery -H_2 gas regulators	www.hpower.com See photograph of the internal components of this unit at: www.usfcc.com/Portable.html
The company is also looking into selling devices – probably of a larger power output - within the domestic market where electricity supply prices are high,	PowerPEM-SSG50: General purpose portable power supply for monitoring apparatus, comms., surveillance and battery charging.	**50W** / 12VoltDC$_{reg}$ Dimensions (cm)≈23×18×29 Weight=5kg	Optional metal-hydride or bottled H_2 supplies	-	
but where natural gas infrastructure exists and the gas prices are low..	PowerPEM-VMS50: Power supply for mobile, variable message road sign.	**50W** / 11-12.5VoltDC Dimensions (cm)=46×32×40 Weight=13.6kg Efficiency≈40% $T_{operation}$=-25 to +45°C @ 15-100%RH	Compressed gas bottles supplying H_2 at 1.6barg, 0.77li/minute. A 4.25m^3 gas supply bottle will power a display sign for 12 days	-	50 units have been operating since 1998.
Additionally, "The Energy Co-Operative Inc." has promised to purchase 12,300 stationary units from H-Power over the next few years	PowerPEM-PS250: Emergency power supply for lighting, radio, TV, camping, comms., small vehicle propulsion and battery recharging.	**250W** / 28VoltDC$_{unreg}$ / 24VoltDC$_{reg}$ Dimensions (cm)≈25×16×41 Weight=8.4kg H_2 feed rate=3.75li/minute	-	-	
- total investment ≈$81million	PowerPEM-PS500: Telecomms. Applications, DC-lighting, power tools and hybrid vehicles.	**500W** / 48VoltDC$_{unreg}$ / 12-24VDC$_{reg}$ Dimensions (cm)≈52×45×26 Weight=15.7kg H_2 feed rate=7.5li/minute	-	-	

	E^{PAC}-250: Emergency power & AC-lighting, small refrigerators, security systems and domestic appliances.	**250W** / 100-110-220VAC(50-60Hz) Dimensions (cm)≈34×17×41 Weight=10.5kg H_2 feed rate=3.6li/minute	-	-	
	E^{PAC}-500: Brown-out protection & AC-lighting, sump pumps, auxiliary heater power supply and computer UPS.	**500W** / 100-110-220VAC(50-60Hz) Dimensions (cm)=52×45×26 Weight=18.7kg H_2 feed rate=7.2li/minute	-	-	
H2 ECOnomy A division of SolarEn International Corporation. CA, USA. (Stack manufacturer)	FC-100: Bare, single cell stack assembly	**<4W** / 0.3-1.0Volt Active stack area=5cm^2 Dimensions (cm)=2×10.5∅	None specified	None specified, but DC/DC converters available.	www.h2economy.com "At the beginning of 2002 H_2 ECOnomy will have an assembly line of FC stacks, although small orders can be accepted now" Company is also looking for partners for small vehicle propulsion (1kW) ventures.
	FC-100-2: Bare, dual cell stack assembly	**<40W** / 0.6-2.0Volt active stack area=50cm^2 Dimensions (cm)=13.5×13.5×4			
Heliocentris Energiesysteme GmbH. Berlin, Germany. (Stack and product manufacturer)	Hydro-Genious Professional range: Educational fuel cell systems.	**2.5W** fuel cell~energy systems including solar panels, electrolyser, gas storage and visual display devices.	gH_2 generated in electrolyser unit, powered by solar panels.	Complete energy system mounted on a display panel.	www.heliocentris.com Ref.61
	PS50-2: Portable power supply, road safety lamps.	**50W** / 12VoltDC Dimensions (cm)=23×20×20 Weight=8kg Operating time=12h @ 50W	7.5li Metal-hydride H_2 storage tank containing 500li gas, weight=8.0kg (75Wh/kg, 80Wh/li)	Air pump and cooling fan.	

	HP-series: Heat & power educational fuel cell systems.	**300W$_{electric}$**/500W$_{thermal}$ 12VoltDC or 230VoltAC $T_{operating}$ max +80°C	None specified.	Liquid-cooled stack – to allow thermal energy extraction experimentation.	
Hydrogenics (Stack and product manufacturer)	HyTEF Power Generator:	**5W-200W** / 4-60V / AC-optional Dimensions (cm)≈26×16×18 $T_{operating}$=-50 to +40°C Fully Automatic Operation 80% heat/electrical efficiency	Low-pressure H_2 supply required (any source).	Self-contained ancillaries: -User display & controls -Air intake fan -Power controller	www.hydrogenics.com The company has stack development links with GM.
	H2X Series Fuel Cell Stack: For UPS, telecomms. and remote power applications.	**10W**-25kW stack options	-	Built-in electrolyser optional with these stacks for regenerative operations.	
	HyPORT Power Generator: Battery recharging and AC-power back-up.	**300W** / 24VoltDC – 28VDC$_{unreg}$ <5kW for AC units $T_{operating}$=0 to +40°C	Low-pressure metal-hydride gH_2 store.	Self-contained ancillaries: -User display & controls -Air intake fan -Power controller	
Intelligent Energy Ltd. Loughborough, UK. (Stack and product manufacturer)	Portable Power Units: Ambient pressure power supply systems based on open-cell stacks for a variety of portable power applications, e.g. power tools, remote data logging power module, home use.	10, 25, 60 & 100W power supplies. e.g. 32-cell based product: **60W** (100W peak) / 20Volt / 3Amp Dim.(cm)≈20×15×13 (power system) Weight=1.2kg (stack)… …≈2.4kg (power system + hydride store) $T_{operating}$≈+50°C Fully automatic operation.	120li gH_2 from external metal-hydride bottle store: "Solid H" model–BL-120, Weight=1.2kg including pressure regulator.	Self-contained ancillaries: -Forced-air fans (≈1W), -Power electronics controller with built-in start-up power battery.	www.intelligent-energy.com Company is setting up full-scale production facilities during 2002. Products have seen active field testing in military applications.

IRD A/S Denmark. (Stack manufacturer)	FCS-0.5KW: Bare, closed-cell stack.	**500W** (54W/cell) / 6VoltDC Dimensions (cm)≈14.3×17.5×17.5 Active cell area(cm)=12.5×12.5 (0.7V/cell, 0.5A/cm^2, 350mW/cm^2)	gH_2, max.2.5bar	None specified (possibly requires compressed air supply)	www.ird.dk
Materials & Electrochemical Research Corporation (MERCorp.) Ariz.,USA.	Small stacks: Bare stack assemblies made to order for demonstration and research purposes.	**5W-150W** High performance stacks available with composite end plates, weight=500g (total)	None specified, but hydrogen and air to be supplied at "near-atmospheric" pressure.	None supplied	www.mercorp.com
NovArs GmbH. Buchlberg, Germany. (Stack and product manufacturer)	70W Fuel Cell System: Experimental demonstration unit, developed for US military and portable power supply applications.	12 cell stack: **70W** (peak 90W) / 7.2VoltDC Dimensions (cm)=7×6.8∅ Weight=223g (stack=103g)	$NaBH_4$ store/reactor: Dim.(cm)=16×8×22, Capacity=220Wh (200Wh/kg), gH_2 held at 2bar, system weight=1.1kg.	Cylindrical, air-cooled PEM unit.	www.novars.com "Available upon request"
Financial partner is Manhattan Scientifics Inc.	Hydrocycle Fuel Cell: To power hub motor unit on bicycle.	40 cell stack: **600W** / 24VoltDC Dimensions (cm)=13×11∅ Weight=780kg… …(1.14li, 590W/li, 860W/kg) $T_{operating}$≈+60°C	Compressed gH_2 bottle (1.36kg), fitted with pressure reducer (900g).	-Blowers (8W, 360g), -Gas valve (160g), -Micro-processor.	Hydrocycle is commercially distributed by Aprilia S.p.A. An electric scooter, using a 3kW fuel cell power supply, has also been demonstrated.
Nuvera Fuel Cells – Europe DeNora Group. Italy. (Stack manufacturer)	Bare, closed-cell stacks	**100W**-3000W stacks / 10-50Amp Power Density≈3kg/kW Dimensions (cm)=15×12×scalable	None specified	Lower power units are air cooled	www.denora.com /our_products/Fuel_cells History of fuel cell manufacture since 1993.

Paul Scherrer Institut with **Engineering College of Grenchen/Solothurn** Villigen, Switzerland. (Stack and product manufacturer)	Autonomous power pack: Open-cell, H2/air-breathing power pack.	20-cell stack: **300W** Dimensions (cm)≈18×15×15 (stack only)	None specified	http://ecl.web.psi.ch/fuelcell/index.html#stacks A series of 100W H_2/O_2 PEFC Power Packs were demonstrated in 1997 and delivered to engineering colleges in Switzerland. A small series of 300W systems are being assembled and will be delivered to various "customers" within Switzerland.
Current Status of Fuel Cell Technology: ***COMMERCIAL DMFC PRODUCTS "AVAILABLE".***				
Smart Fuel Cell Germany	25W self-sufficient portable power packs for traffic/camera power.	**25W** / 12V Dimensions 120 x 160 x 170mm Weight 2.8kg Estimated unit costs of 3-5$ each.	Liquid Methanol (125ml) Dimensions (mm) 100 x 40 x 55 Weight 190g	Water management system of unspecified design www.smartfuelcell.com

Table 5 - Current Status Of Fuel Cell Technology: Commercial Products "Available"

ORGANISATION	PRODUCT	SPECIFICATION	HYDROGEN SOURCE	FUEL CELL SYSTEM ANCILLARIES	ADDITIONAL INFORMATION
Current Status of Fuel Cell Technology: ***COMMERCIAL PEMFC PRODUCTS "IN PREPARATION".***					
Anuvu Inc. CA, USA. (Stack and product manufacturer) *Recently bought out by Whistler Inc.*	Carbon-X Fuel Cell: Portable power tool and UPS applications.	**<1kW** units Carbon material used widely to reduce stack weight.	Bottled H_2 and O_2 gases supplied to demonstration units.	-	www.anuvu.com Commercial, domestic products planned to be available for 2002.
DAIS-Analytic Corporation. Boston & Tampa, USA. (Stack manufacturer – products in planing)	DAC-10: Bare, open-cell fuel cell stack.	**10W** (can order 1-20W units) Dimensions (cm)≈4.6×10.2×10.2 Weight<910g, Cost≈$995	gH_2 from compressed gas cylinder suggested.	None specified – stack is advertised as a "passive" device	www.daisanalytic.com All products sold as prototypes. Commercial scale-up of production in progress – awaiting repackaging of existing fuel cell systems.
	DAC-25:	**25W** (nominal) Dimensions (cm)≈5.1×4.6×10.2	-	-Forced-air fan -Fuel pump.	
	DAC-150:	**150W** (peak 200W) Dimensions (cm)≈4.6×10.2×20.3	-	-Forced-air fan -Fuel pump.	
EC-Power Inc. Trading company for Sorapec S.A. products. NY, USA, Fontenay-sous-Bois, France. (Stack manufacturer)	Fuel cell stacks: Mobile applications.	**<2kW** stacks	-	www.ecpowerinc.com Sorapec originated from Nitech – which sold the alkaline battery technology to Duracell. EC-Power has cooperative and licensing agreements with subsidiary of Technicatome S.A. to develop and manufacture complete fuel cell systems for applications related to marine propulsion and urban mass transportation. The Company is currently transitioning from research and development to focusing on commercial production	

Enable **Fuel Cell Corporation** A wholly-owned subsidiary of **DCH Technology Inc.** WI, USA (Stack and product manufacturer)	Enable PFC Flashlight: Integrated open-cell stack to demonstrate the replacement of 6×D-cell batteries by a fuel cell.	**4W** / 7.5Volt Weight≈1kg (≈79Wh/kg, 205mW/cm^3) Operating time=20h	70li gH_2 (81Wh) supplied from integrated metal-hydride bottle.	None specified – stacks are “passive” devices, requiring no forced air/O_2 supply or cooling	www.dcht.com
	Enable PFC: Packaged, open-cell stack for portable power applications e.g. scoters, bikes, wheel chairs, lighting, comms. etc.	**<100W** / 3, 6, 12 or 24VoltDC / <10A Dimensions (cm)=scalable e.g. 12W unit≈15×7∅ 1.5W unit≈6.4×3.2∅ Weight>57g Efficiency=50-57%	Bottled gH_2 from either compressed gas or metal-hydride store. e.g. DCH metal hydride bottle and regulating valve (≈20cm tall).		
*Enable was created to commercialise fuel cell technology licensed from **LANL**.*	DCH Remote Power Supply: For unsupervised data-logging and comms. field equipment.	**15W** / 12VoltDC$_{regulated}$ Dimensions (cm)≈15×15×25 Weight≈910g Operating time=135h @ 12V, 0.4A	500li gH_2 from metal-hydride source.	Self-contained unit.	This power supply is used by MeteoStar to power remote data logging equipment and satellite up-link communicators.
Fuel Cell Consultants Switzerland Ulf Bossel (Fuel Cell Consultant)	Portable Power Supply: Portable power pack for outdoor camping uses and battery re-charging.	**20W** / 12VoltDC Dimensions (cm)=16×6.8∅(stack only) Weight=1.5kg(complete unit)	3×compressed gH_2 bottles carried within unit case.	Self-contained unit within carry case.	20 units already manufactured for development trials and schools training equipment. Ref.62

Palcan Fuel Cell Company Ltd. British Columbia, Canada. (Stack and product manufacturer) *Cosworth Minerals Ltd. has been attempting a buy-out of all Palcan's shares in a reverse take-over, 02-2001.*	Palpac Power Systems: Small-vehicle and portable power supply units.	**300W**-1000W systems H_2 gas & air breathing.	H_2 stored in metal-hydride canisters. Palcan is attempting to set up regional/chain H_2 canister refuelling-exchange networks.	-	www.palcan.com Range of Palpac power supply systems in development. An electrically propelled bicycle has been demonstrated, and this technology has received interest from China.
Current Status of Fuel Cell Technology: COMMERCIAL SOFC PRODUCTS "IN PREPARATION".					
Adelan UK	Micro-tubular SOFC stack	**100W - 10kW**	Natural Gas supply		www.adelan.co.uk

Table 6 - Current Status Of Fuel Cell Technology: Commercial Products "In Preparation"

ORGANISATION	PRODUCT	SPECIFICATION	HYDROGEN SOURCE	FUEL CELL SYSTEM ANCILLARIES	ADDITIONAL INFORMATION
Current Status of Fuel Cell Technology: ***PEMFC PRODUCTS IN “R&D” or “DEMONSTRATION” PHASE.***					
Alcatel CIT. Paris, France. (Telecoms. provider)	Showcase Fuel Cell Energy System: For remote powering of telecommunication equipment.	Hybrid fuel cell~solar PV~electrolyser~ battery energy system. **200W** (rated) / ≈48Volt System can generate 3.6kWh/day.	gH_2 Internally sourced from solar-PV powered electrolyser unit.	-	This FIRST demonstration project began in March 2000. Ref. 63
Ballard Power Systems Inc. Vancouver, BC, Canada. (Stack and product manufacturer)	Demonstration unit:	**100W** portable power supply.	-	-	Ref. 64
Case Western Reserve University OH, USA.	Miniature Fuel Cells: On-board computer and electronics equipment power supply.	?W – possibly in the **10mW** range Dimensions (cm)≈0.5×0.5×0.5	Possibly a DMFC device.	-	www.cwru.edu/menu/research/fuelcells.htm http://electrochem.cwru.edu/yeager/research.htm Research funded through a DARPA grant.
CEA-Grenoble Grenoble, France.	Flat, Poly-element Fuel Cell: For integration onto circuit-boards.	3 & 4-cell planes: **500mW** / 2VoltDC / >170mAmp (800mW peak power / 1.5V / 0.5A)	Bottled gH_2 (5li/h) & gO_2 supplies required, with humidification via bubbling through water.	-	Ref. 65

Defence and Advanced Research Project Agency – (DARPA) DoD, USA.	"Palm Power": **20W** / 12VoltDC devices. Project for developing field-demonstration models of small, portable, military power units for e.g. radio comms.		Two storage systems under investigation include Aluminium-hydride (2%wt) and Ammonia-Lithium-Aluminium-hydride (5%wt).	http://www.darpa.mil/dso/thrust/md/palmpower http://www.darpa.mil/dso/thrust/md/ees_1b.htm Contact Person: Dr.Robert Novak, Defence Sciences Office.	
Trials of the Ball Aerospace and H-Power devices have also been reported by the US-Army Communications and Electronics Command – (CECOM)	"Portable Power": 50 to 500W with CHP option devices. Project for larger power, portable devices for field demonstration as e.g. battery re-charging units, encampment heating and lighting.		Reforming of strategic fuels (Diesel, Jet Fuel) necessary for these devices.	DARPA supports the two-way transition of technologies used to develop military and commercial products – e.g. Ball Aerospace and H-Power have been linked to DARPA projects. Ref. 66	
Electronic Engineering Technology Div., Laurence Livermore National Laboratories DoE, USA.	MEMS-Based PEMFC: For battery replacement in portable sensors and comms.	**1W**-20W / 3VoltDC / ≈300mA/cm^2 "Thin film" 0.5W to 50W devices also proposed*.	gH_2 delivered from methanol reformer or direct gas storage.	DoE Contract No.: W-7405-Eng-48. Ref. 67 *See: www.llnl.gov/IPandC/Technology/cbd/minifc.html	
ENEA-CRC Italy.	Portable Demonstration Generator:	Nuvera 150W PEM stack system: **74W** / 13.5VoltDC / 5.5Amp "Air-breathing", air-cooled Fully automatic operation Efficiency≈25%	1li, 150lb compressed gH_2 bottle supply. Feed rate=104li/h.	Unit contains: -DeNora/Nuvera E-AN3 stack (150W, 12.6V, 12A, 1.2b air supply to cathode, T_{outlet}<60 C),, -Compressor KNF N811 (12V, 1A, 8li/min@1.3b), -Valves (12V, 0.7A), -DC/DC Converter (8-35V_{in}, 12V_{out}@4A), -PLC (24V@0.4A).	www.enea.it Ref. 68
	Bicycle-range Extender:	Nuvera **300W** fuel cell system: Automatic start-up operation.	200b gH_2 compressed bottle gas supply.	Volumetric air compressor.	Ref. 69

Energy & Resources Lab., Industrial Technology Research Institute with **National Tsing Hua University** Taiwan.	Flat, air-breathing PEMFC:	?W 100mW/cm^2 Weight≈300g	Dry gH_2 supply.	None required for cooling or humidification.	Ref. 70
	Small PEMFC System: Demonstration of experimental model.	Single-cell stack, MEA=5cm×5cm: gO_2 + gH_2 supply: 0.81-0.76Volt / 100-200mA/cm^2 Air + gH_2 supply: 0.75-0.66Volt / 100-200mA/cm^2	32g gH_2 from $LaNi_5$ store (12Ah).	Funding was received from the Energy Comm., Ministry of Economic Affairs, Rep. of China – Fuel Cell Project. Ref. 71	
Fraunhoffer Institute for Solar Energy Systems. Freiburg, Germany.	Banded Fuel Cell: For camcorder.	16-cells: **10W** / 8Volt Dimensions (cm)=4.6×2.6×2.4 Electrical efficiency>50%	gH_2 or Methanol fuels.	-	www.ise.fhg.de Demonstrated in 1998 – cost effective production suggested.
	Banded Fuel Cell: For portable PC.	25-cells in 5×5 planar arrangement: **20W** / 200Wh/li (inc. fuel storte) 0.7V to 12V DC/DC conversion possible for single-cell devices 400Wh/li possible with optimal system packaging.	-	3×minature ventilators for oxygen & water transport.	Ref. 72
Fuel Cell Research Centre, Korea Institute of Energy Resources. Korea.	Air-Breathing PEM Development:	Single, open-cell stack ?W 322mW/cm^2 / 0.5VoltDC 645mAmp/cm^2	-	Operation limited by water removal from the cathode.	Ref. 73

IdaTech LLC. Oregon, USA. (Stack and product manufacturer)	Recreational Fuel Cell Systems: For camping, small vehicle and boat applications.	Both open-cell & closed-cell systems have been demonstrated: **500W**–1kW Hot water recovery available from higher-power, closed-cell models.	gH_2 from reformed methanol, camping propane gas cylinders or other liquid hydrocarbons using in-board reforming system.	Smaller, lower-power systems most likely to be naturally air-cooled stacks. Fuel reformer built into the system.	www.idatech.com Ref. 74
Motorola Integrated Electronic Systems. Georgia, USA. (Product manufacturer)	Planar Fuel Cell: For portable, hand-held devices.	**7.2W** / 3.6VoltDC / 2Amp Dimensions (cm)=5×8.5×1.3 For 0.038li gH_2/86Wh energy supply: …relates to operation at 19Ah @ 3.6V	Supply options (0.038li): Compressed gH_2 Metal-hydride store Carbon nano-tube store Fuel reformer: Dimens(cm)=6×12.3×2.6	Ref. 75 www.motorola.com/mediacenter/news/detail/0,1958,468_244_23,00.html www.motorola.com/ies/ESG/index.html	
NASA Glen Research Centre – (GRC) OH, USA. With **Energizer Holdings Inc.** MO, USA. (Battery manufacturer)	Unitised Regenerative Fuel Cell (URFC) – a Micro-Electro-Mechanical-System (MEMS): Miniature power supply for micro-spacecraft, cellular phones, PCs and hearing aids.	?W – possibly in the 10mW range >200Wh/kg Dimensions AA battery (2-3mm thick) Weight≈14g	Regenerative fuel cell capabilities allowing on-chip fuel storage.	All components built onto silicon or ceramic wafer.	Energizer has agreed to assist GRC with evaluation of the MEMS URFC. Commercialisation of the device will be arranged through the GRC Commercial Technology Office: http://technology.grc.nasa.gov/tech/tops/pg.htm Product development is being carried out at **Case Western Reserve University**.
NedStack B.V. Netherlands.	-	?W	-	-	www.nedstack.com
Protonex Technonogy Corp. MA, USA. (Product manufacturer)	Small, portable fuel cell power systems.	?W Developing simpler stack integration and sealing methods to bring down manufacturing costs.	-	www.protonex.com Ref. 76	

Samsung Advanced Institute of Technology – (SAIT) Korea. (Product manufacturer)	Demonstration unit: Power supply for notebook PC.	**40W** / 12VoltDC / 3.3Amp Dimensions (cm)≈2.5×6×6 Weight=90g (450W/kg, 150Wh/kg) Operating time=6h	gH_2 from metal-hydride store.	-	www.sait.samsung.co.kr/newsait Product development is being carried out in collaboration with **The Fraunhoffer Institute.**
US-Army CECOM USA.	Hybrid system trials for military radio comm. equipment operating with pulsed power loads.	Ball Aerospace fuel cell: Fuel Cell: **25W** / 6-cell / 4.0VoltDC Boulder Technologies Thin Metal Foil lead-acid battery (2 units), each: 4VoltDC / 1.2Ah / 8kW/kg Dimensions (cm)≈7×2.3∅ Weight≈82g 7-minute recharge time.	gH_2 compressed gas bottle, delivering at 1psig.	Hybridisation required in order to allow rapid power-up of field communication equipment operating with periodic power pulses of 18W/2.5W. Batteries support initial 2.5 minutes of operation whilst fuel cell completes power-up sequence. Ref. 77	
	Hybrid system trials for military radio comm. equipment operating with pulsed power loads.	Ball Aerospace fuel cell: Fuel Cell: **25W** / 6-cell / 4.0VoltDC Panasonic "Gold" Capacitor bank: 5Volt / 70Farad capacitor bank	gH_2 compressed gas bottle, delivering at 1psig.	Hybridisation required in order to allow rapid power-up of field communication equipment operating with periodic power pulses of 18W (2mins) / 2.5W (18mins). Capacitors support initial 1-8.5 minutes of operation whilst fuel cell completes power-up sequence. Ref. 78	
Zentrum für Sonnenenergie- und Wasserstoff-Forschung – (ZSW) Stuttgart, Germany.	Prototype System 1:	20-cell stack **150W** output (250W total) / 12VoltDC 650W output with humidification Active cell area=100cm^2 Stack dimensions (cm)≈19×12×12 System dimensions (cm)≈35×35×35 $T_{operation}$<40 C – heat exch. Limit.	2li Metal-hydride store, delivering 400li gH_2.	Self-contained ancillaries (consuming 100W): -Air pump -Coolant pump -H_2 circulation pump -Micro-controller -Pressure regulator.	www.zsw-bw.de Ref. 79

	Prototype System 2:	250W (400W peak for 15mins) Dimensions (cm)=45×32×40 Auto-start and shutdown.	-	Minimised ancillaries (consuming 15W): -Air blower -Cooling fans (self-humidifying through air recirculation).	
Current Status of Fuel Cell Technology: DMFC PRODUCTS IN “R&D” or “DEMONSTRATION” PHASE.					
Toshiba Tokyo, Japan	DMFC for PDA, Mobile Phones	**5-8W** demonstration unit Dimensions (cm) = 12.7 x 10.5 x 2.5 Weight (kg) = 0.5	Internal methanol and water tanks	Fuel pumps	Market entry predicted by 2003. 10% fuel crossover, no mitigation observed

Table 7 - Current Status Of Fuel Cell Technology: Products In “R&D” Or “Demonstration” Phase

B APPENDIX B - APPLICABILITY OF FUEL CELL TECHNOLOGY

Applications in the Power Range: <10mW to 1W

Market / Application	Existing Power Sources	Portable Power Source Operating Constraints	Fuel Cell Applicability & Fuel Options
Calculators	Primary batteries PV/battery-hybrid	Dimensions (mm)<50×15∅ Lifetime>2years between battery replacement	Not competitive on size, cost or operating lifetime between refuelling.
Electronic memory back-up power	Primary batteries Rechargeable batteries	Dimensions (mm)<10×20∅ Lifetime>2years continuous battery operation. Needs to supply minute current to solid-state memory chips in order to retain data stored as electric charge. Will need to operate when the host device's power supply is cut off during, e.g., transit or storage.	Flat/planar fuel cell devices are in R&D and product preparation phases for such applications. Fuel supply options include life-time, on-board supplies of gH_2 from bottled gas or from hybrid, regenerative electrolyser systems.
Hearing aid	Primary batteries	Dimensions (mm)<3×10∅ Lifetime>3-4 weeks between battery replacement. Must be small enough to fit inside a device that is worn in or close to human ear. Consumers may be willing to pay a premium for an advanced power source.	Not competitive on size. Emissions could be a problem for the wearer. The hydrogen source would need to be extremely compact and temperature stable so as not to cause discomfort in/around the ear.
Miniature radio receivers	Primary batteries Rechargeable batteries Mechanical (clockwork)	Dimensions (mm)<50×30×20 Lifetime>1month between battery replacement. Low cost and compactness are the two main competing issues.	Not competitive on cost or size. Size is primarily an issue of the method of hydrogen storage, but even miniaturised metal-hydride stores will be too expensive for this type of product application. Exhaust issues to be considered. Very useful product for educational demonstrations.
Mobile Phone	Rechargeable batteries	Dimensions (mm)<70×35×10 Lifetime>2days between battery recharging. Must be compact and offer long operating times. Consumers may be willing to pay a premium for an advanced power source.	Not competitive on cost or size. Size is an issue of the method of hydrogen storage, for which miniaturised compressed hydrogen bottles, metal-hydride stores or even carbon-nanotubes may be economically viable. Exhaust issues to be considered. A wearable fuel cell holster for battery recharging is considered as an option.

Pacemaker	Radio-thermal Primary batteries	Dimensions (mm)<20×40∅ Lifetime>8years between battery replacement. Must operate in an hermetically sealed capsule	Not applicable unless fuels can be derived from bodily fluids, and exhaust products treated similarly. Interfaces to human tissues would have to be made of human-compatible tissues/materials so as not to provoke an immune response.
Personal Digital Assistants/Electronic Organisers	Rechargeable batteries	Dimensions (mm)<70×35×10 Lifetime>1 day between battery recharging. Must be compact, but offer long operating times.	Not competitive on cost or size. Size is an issue of the method of hydrogen storage, and miniaturised metal-hydride stores may still be too expensive an option for this product application. Exhaust issues to be considered.
Solid-state sensors and portable detectors	Primary batteries Rechargeable batteries	Dimensions (mm)<50×30×20 Lifetime>6months between battery replacement. Must have a stable voltage output.	Not competitive on size or cost, but could offer competitive operating life-time advantages in higher value goods, e.g. radiation detectors, weather stations. Fuel source is most likely to be miniature compressed hydrogen bottles or metal-hydride stores.
Watches	Primary batteries Mechanical	Dimensions (mm)<3×10∅ Lifetime>2years continuous battery operation. May need to operate in an hermetically sealed casing and underwater.	Not competitive on size. The operating lifetime of the existing battery technology is comparable to the lifetime of the product – which negates the requirement for a rechargeable/refuelable power source.

Table 8 - Applications in the Power Range: <10mW to 1W

Applications in the Power Range: >1W to 10W

Market / Application	Existing Power Sources	Portable Power Source Operating Constraints	Fuel Cell Applicability & Fuel Options
Advanced mobile phone/communicator	Rechargeable batteries	Dimensions (mm)<70×35×10 Lifetime>1day between battery recharging. Must be compact and offer long operating times. Consumers may be willing to pay more for an advanced power source.	Not competitive on cost or size. Size is an issue of the method of hydrogen storage, Exhaust issues to be considered. A wearable fuel cell holster for battery recharging is considered as an option.
Camcorder	Rechargeable batteries	Dimensions (mm)<70×35×10 Lifetime>8hours between battery recharging. Must be compact and offer long operating times. Consumers may be willing to pay a premium for an advanced power source.	Not competitive on cost. Size is an issue of the method of hydrogen storage, though demonstrated devices appear to show an early competitive potential. Miniaturised hydrogen storage may be economically viable in this application. Exhaust issues to be considered.
Micro-satellite power	PV/battery-hybrid	Dimensions (mm)<50×30∅ PV array ≈ 50mm×50mm Lifetime>1year continuous operation. Development funding from the space research community may help to bring product costs down.	Both fuel and oxidant stores will need to be built into the complete power system. The fuel/oxidant supply cannot be recharged in space, but a smaller storage capacity or longer operating time could be realised in a hybrid PV/electrolyser system.
Palm-top Computers	Rechargeable batteries	Dimensions (mm)<100×15∅ Lifetime>1day between battery recharging. Must be compact and offer long operating times. Consumers may be willing to pay more for an advanced power source.	Not competitive on cost or size. Planar/flat fuel cells could be developed with higher power outputs for this application. These would need a correspondingly miniaturised fuel store, possibly of the carbon nanotube type.
Safety lamps & flashlights	Primary batteries Rechargeable batteries Hydrocarbons	Dimensions (mm)<150×60×30 Lifetime>5days between battery recharging. Must be robust enough to withstand extreme outdoor conditions with little environmental protection.	Not competitive on cost, but some devices already comparable on size and exceeding the operating lifetime criterion. If faultless operation is a high priority, it may be possible that a premium price could be tolerated for an advanced power source.
Transistor radio	Primary batteries Rechargeable batteries	Dimensions (mm)<100×25×15 Lifetime>2weeks between battery recharging. Low cost and compactness are the two main competing issues.	Not competitive on cost or size. Size is primarily an issue of the method of hydrogen storage, but even miniaturised metal-hydride stores will be too expensive for this type of product application. Externally connected power supplies are available at a premium.

Table 9 - Applications in the Power Range: >1W to 10W

Applications in the Power Range: >10W to 100W

Market / Application	Existing Power Sources	Portable Power Source Operating Constraints	Fuel Cell Applicability & Fuel Options
Battery re-charger	Primary batteries Vehicle battery AC mains (non-remote)	Dimensions (mm)<200×150×100 Weight<3kg Must be able to cope with continuous battery recharging periods of up to 8hours.	Niche market for fuel cell devices, though mainly for higher power recharging applications. For small, portable, consumer goods, it may be more cost effective to revert to non-rechargeable batteries for short-term, remote operations. Available fuel cell devices are, currently, quite bulky.
Hand-held power tools	Rechargeable batteries	Dimensions (mm)<120×80×80 Weight<1kg Lifetime>30minutes continuous operation.	Not competitive on cost or size. Demonstrated open-cell devices cannot, yet, fit inside the target consumer product, but may be acceptable as an externally connected power supply in some cases. Miniaturised fuel stores would also be desirable, but existing, small, externally mounted, compressed gas bottles and metal-hydride stores may be acceptable.
Mobile, variable road sign	Rechargeable batteries ICE Gen set	Dimensions (mm)<500×500×500 Weight<60kg Lifetime>5days operation.	Not competitive on cost, but some devices already comparable on size and exceeding the operating lifetime criterion. If faultless operation is a high priority, it may be possible that a premium price could be tolerated for an advanced power source. Standard, compressed gas bottles suitable for this application.
Outdoor/Camping power supply	Primary batteries/ ICE Gen set	Dimensions (mm)<300×200×200 Weight<30kg Lifetime>5days operation Consumers may be willing to pay a premium for a silent operation power supply that is less bulky and lighter in weight than a battery pack.	Potential niche market for fuel cell devices, though mainly for higher power applications as replacements for ICE systems. For small, portable, consumer goods, it may be more cost effective to revert to non-rechargeable batteries for short-term, remote operations as available fuel cell devices are, currently, quite bulky.
Portable PC/Notebook	Rechargeable batteries	Dimensions (mm)<150×100×30 Weight<1kg Lifetime>5hours continuous operation. Consumers may be willing to pay a premium for an advanced power source.	Not competitive on cost or size. Demonstrated open-cell devices cannot, yet, fit inside the target consumer product, but may be acceptable as an externally connected power supply in some cases. Miniaturised fuel stores would be very desirable. A premium may be paid for advanced storage systems, possibly of the carbon nanotube or miniature methanol reformer type.

Radio communicators	Rechargeable batteries	Dimensions (mm)<100×50×50 Weight<1kg Lifetime>1day operation between recharging.	Increasingly competitive on cost and size. Demonstrated open-cell devices cannot, yet, fit inside the hand-held part of the consumer product, but may be acceptable as an externally connected power supply in many cases – e.g. as a wearable power supply pack. Miniaturised fuel stores would also be desirable, but existing, small, externally mounted, compressed gas bottles and metal-hydride stores may be acceptable. Use of fuel cell devices to recharge existing, built-in, battery power sources is a considered option in this target market. In trials, fuel cell devices have out-performed rechargeable batteries on weight and operating time requirements, and can be cost-competitive.
Surveillance cameras	Rechargeable batteries PV/battery-hybrid	Dimensions (mm)<300×200×200 Weight<30kg Lifetime>5days continuous operation.	Niche market for fuel cell devices. For low-powered equipment it may be more cost effective to revert to non-rechargeable batteries for short-term, remote operations. Available fuel cell devices are, currently, quite bulky.

Table 10 - Applications in the Power Range: >10W to 100W

Applications in the Power Range: >100W to 500W

Market / Application	Existing Power Sources	Portable Power Source Operating Constraints	Fuel Cell Applicability & Fuel Options
Domestic gardening equipment	Mechanical ICE AC mains (non-remote)	Dimensions (mm)<300×200×200 Weight<20kg Lifetime>1hour continuous operation. Silent and cordless operation may be desirable.	Not competitive on cost, or size for smaller items of equipment with built-in power units. Fuel cell devices may be used in some sit-on lawn mower applications – but these would fall under the motive/propulsion device category.
Domestic power supply back-up	ICE Gen set Rechargeable batteries	Dimensions (mm)<500×500×200 Weight<60kg Lifetime>2hours continuous operation. Silent and odourless operation would be desirable.	Niche market for fuel cell devices, uniquely positioned to act as portable power supplies that could be carried/wheeled around and operated within a domestic environment. These devices could offer UPS or power conditioning functions if interfaced with the existing AC-mains supply. Compressed gas stores or diesel/propane fuel reformers suitable for this application.
Heavy-duty battery recharging	ICE Gen set AC mains (non-remote)	Dimensions (mm)<400×400×300 Weight<30kg Must be able to cope with heavy duty recharging periods of up to 8hours. Silent operation may be desirable.	Niche market appears to be military-lead at present, where silent and low-infra-red emission operation is highly desirable. Commercial applications may include emergency vehicle battery boosting and professional expedition equipment recharging. Bottled, compressed gas stores suitable for these applications.
Professional Power tools	Rechargeable batteries ICE Gen set	Dimensions (mm)<150×100×100 Weight<1.5kg Lifetime>1 hour continuous operation	Not competitive on cost, or size for products with built-in power sources. Demonstrated open-cell devices cannot, yet, fit inside certain target consumer products, but may be acceptable as an externally connected power supply in some cases. Miniaturised fuel stores or methanol/fuel would also be desirable.
Telecommunication field equipment	Rechargeable batteries PV/battery-hybrid ICE Gen set	Dimensions (mm)<400×400×300 Weight<30kg Lifetime>3days continuous operation. Must withstand harsh outdoor conditions and, ideally, able to interact with renewable energy hybrid systems.	The higher energy conversion efficiency of fuel cells gives these devices an operating endurance advantage over ICE generator sets, and may be more easily transportable than heavy battery banks. Compact power units may use bottled, compressed gas stores or house a Diesel/propane fuel reformer. Advanced, hybrid power supplies may comprise solar-PV, wind-turbine and regenerative electrolyser units.

Table 11 - Applications in the Power Range: >100W to 500W

C APPENDIX C - KEY UK PLAYERS IN THE DEVELOPMENT OF FUEL CELL TECHNOLOGY

Organisation	Primary Area of Interest	Market Interests
Generics	PEM/DMFC	Technology consultants/Novel fuel cell design
Intelligent Energy	PEM	Battery/Fuel Cell hybrids for portable applications
QinetiQ	PEM/DMFC	Portable power for military and commercial applications
Newcastle University	DMFC	Fundamental research into methanol fuelled systems particularly modelling and catalysis
Johnson Matthey	PEM/Fuel Processing	Catalyst and membrane development
Adelan	SOFC Tubular	Micro Tubular SOFC Systems
Ceres Power	SOFC Planar	Portable generators in the kilowatt range
Imperial College	SOFC	Fundamental research into ceramic ion conduction
Rolls Royce	SOFC	Pressurised hybrid fuel cell system at around the 1MW size range.
Accentus	Fuel Processing	Advanced fuel reforming systems
Wellmans CJB	Fuel Processing	Development of reforming and gas clean-up technologies

Table 12 - Key UK Players in the Development of Fuel Cell Technology

D APPENDIX D - WORLD-WIDE PLAYERS IN THE DEVELOPMENT OF FUEL CELL TECHNOLOGY

Organisation	Primary Area of Interest	Market Interests	Notable Successes
Ballard	Canada/PEM	Commercialisation of PEM Technology	Recently unveiled a 1.2kW portable power generator for intermittent operation (few hours/week) and is seeking commercial partners.
Enable Fuel Cell Corporation / DCH Technology Inc.	USA/PEM	Enable was created to commercialise fuel cell technology licensed from LANL.	Enable PFC Flashlight: Integrated open-cell stack to demonstrate the replacement of 6×D-cell batteries by a fuel cell
Fraunhofer Institute for Solar Energy Systems	Germany/PEM	250mW to 250W, banded structure PEMFCs	The researchers have demonstrated a hydride fuelled miniature fuel cell which allows operation for up to 10 hours at similar volumes and weights as conventional batteries.
H-Power Corp.	USA/PEM	Stack and product manufacturer	"The Energy Co-Operative Inc." has promised to purchase 12,300 stationary units from H-Power over the next few years – total investment≈$81million
Hydrogenics	USA/PEM	Stacks developed for UPS, telecommunications and remote power applications.	The company has stack development links with GM.
Novars	Germany/PEM	Portable fuel cells for electric motors	Hydrocycle, a prototype electric bicycle powered by a fuel cell stack that produces a power output of 170 W. A 670W unit is being tested on vacuum cleaners by Electrolux.
Siemens AG	Germany/PEM	Transport and stationary power	Collaborated with HDW to develop ~34kW modules for submarine applications.
Manhatten Scientific	USA/DMFC	Portable fuel cells for computer power	Micro fuel cell concept.
Medis	Israel/DMFC	Alcohol fuelled mobile phone and laptop computer power units.	Claims proprietary liquid electrolyte capable of delivering 450Wh/kg. Estimates costs at 9-15$ for laptop computer power unit.

Smart Fuel Cells	Germany/DMFC	Small Scale Power	Prototype portable power packs for applications in the 40W range. Low densities caused by water management issues (61.2Wh/kg, 73.6Wh/l). Estimated unit costs of 3-5$ each.
Toshiba	Japan/DMFC	Hand held devices, PDA, Mobile Phones	Prototype PDA power base unit. Supplies 5-8W, from internal water/methanol tanks. Cell size ~10cm3, unit size ~1/3 of a litre. They estimate that it shall be on the market by 2003.
Global Themoelectric	Canada/SOFC	Transport, stationary power	Working with Delphi/BMW in the development of a gasoline powered 5kW onboard APU.
Siemens-Westinghouse	Germany/ SOFC	Large stationary power	100kW CHP demonstrator running for ~20,000 hours. 250kW & 1MW units in preparation.
Sulzer Hexis	Sweden/SOFC	Small scale residential power	1kW residential unit
Battelle	USA/ Nanotechnology	Microscale fuel processor	Construction of a 500mW butane/methanol steam reformer with a volume of less then $0.5mm^3$
Case Western Reserve University	USA/Nanotechnology	Fuel cell on a chip	Micro-fabricated fuel cells have been constructed and tested with a self contained hydrogen source based on sodium borohydride. Reproducible steady-state power outputs of $2mW/cm^2$ have been achieved.
LeHigh University	USA/ /Nanotechnology	Chip based micro-chemical plant	Hydrocarbon fuelled silicon micro-reformer $\sim 3cm^2$ producing hydrogen.
Motorola	USA/Nanotechnology	Microscale DMFC	Ceramic construct incorporating fuel delivery and exhaust micro-channels as well as micro-engineered pumps and control systems. Device is roughly $50cm^3$ (excluding fuel and electronics) and delivers 100mW.
PNNL	USA/ Nanotechnology	Micro-channel fuel reformers for man portable applications	10W butane fuel processor and fuel cell system capable of delivering 1,680Wh. The system weighs ~0.7kg and has a volume of roughly one litre. This corresponds to an energy density of 2360Wh/kg far surpassing the available battery technology (Li-Ion ~300Wh/kg).

Table 13 - World-Wide Players in the Development of Fuel Cell Technology

Organisation	Location	Primary Area of Interest	Market Interests
Victrex Plc	UK	Polymeric materials	At the forefront of high performance polymer technology and responsible for the development of a number of new materials eg PEEK polymer. They are currently working with Ballard on ionomer development.
Johnson Matthey	UK	Speciality Chemicals	Their fuel cell division was formed in April 2000 to further their interests in MEA technology with primary involvement in the development and manufacture of catalysts for fuel processing or low temp. fuel cells.
Morgan Fuel Cell	UK	Graphitic materials	Formed in 2001 based upon the previous experience of Morgan Speciality Graphite they specialise in the development and supply of bipolar plates and gas diffusion layers.
Ballard	Canada	PEM Commercialisation	Ballard are committed to the commercialisation of PEM technology and have through process of acquisition or strategic partnership gained capability in all areas of PEM fuel cell manufacture.
De Nora (E-Tek)	Europe	Carbon Diffusion Layers, Catalysts	Based upon their experience in the chloro-alkali industry, De Nora expanded into PEM fuel cell development. Their recent acquisition of E-TEK has added experience of gas diffusion electrode technology.
Du Pont	USA	Chemicals Manufacturer	Manufactures Nafion membranes for use in PEM fuel cells. It also has interests in the development of MEA's and bipolar plates. It is currently involved with Mechanical Technologies to commercialise DMFC systems
Engelhard Corporation	USA	Catalyst Development	Collaborating with Plug Power through the development of advanced catalysts. Also involved in a number of similar technology programmes with other fuel cell developers.
UCAR	USA	Graphite Supplier	Union Carbide is the manufacturer of the flexible graphite gasket material Grafiol which is a key material in the fabrication of flow field plates for PEM fuel cells.
W L Gore	USA	Fluoropolymer materials	Supplier of a range of commercial fluoropolymer products ranging from' breathable' waterproof clothes to assorted filtration membranes. It has marketed its own brand of MEAs since 1997 under the PRIMEA brand.
Ceram Research	UK	Ceramic Processing	Involved in a number of projects relating to the design and manufacture of SOFC stacks. These include materials and electrode development, reforming catalysts and fabrication techniques for planar and tubular systems.
Advanced Ceramics Ltd	UK	Ceramic Processing	Advanced Ceramics is involved in the manufacture of specialised ceramic materials for power applications such as thermoelectrics or SOFC components.
InDEC Ltd	Netherlands	SOFC Components	A subsidiary of the Netherlands Energy Research Foundation (ECN) 'Innovative Dutch Electro Ceramics' was founded in 1999. Main business is the high-volume manufacture of quality planar SOFC components.

Table 14 - Major Fuel Cell Component Manufacturers

E APPENDIX E - RISK MATRIX FOR FUEL CELL POWERED DEVICES

Risk	Outcome	Likelihood in Normal Operation	Severity	Mitigation
Fuel / Air Mixing	Failure of membrane or seals leads to formation of explosive mixture.	*Medium to High* It is difficult to predict or completely prevent the degradation of the membrane with time. It is unlikely that, the failure will result in more than the formation of a small pinhole or crack thus the potential for explosion is reduced.	*Low* At this scale it is unlikely to result in more than a 'popping' noise.	*Medium* Automatic control values will prevent flashback to the fuel source.
High Pressure Cylinder	Cylinder is vented through accident or mishandling	*Low* Cylinders are generally robust enough for everyday usage but currently not user-friendly.	*Very High* The remaining gas will be released in a powerful jet that has the possibility of self-ignition.	*High* Users must be made aware of the dangers and educated in how to avoid them.
Hydride Container	Hydride container is vented through accident or mishandling	*Low* Containers are generally robust enough for everyday usage but currently not user-friendly.	*Medium* While the properties of hydride systems ensure a controlled release of hydrogen under these conditions this could lead to a build up of potentially explosive gas. If the hydride is air-sensitive this could initiate combustion.	*Medium* Users must be made aware of the dangers and educated in how to avoid them. Restrict choice of hydrides.
Anode Leakage (H_2)	Fuel leaks from anode side	*Medium* Gas connections are typically pressure tested before use and as such are suitability robust. Hydrogen is however a small molecule and diffuses readily.	*Medium* Depending on the rate of leakage and the nature of the surroundings this could lead to a build up of potentially explosive gas.	*Low* External hydrogen sensors could monitor any potential leakage.
Anode Leakage (Methanol)	Methanol fuel leaks from anode side	*Medium* The CO_2 produced on the anode side will contain methanol. Care must be taken when venting this.	*High* Release and build up of toxic vapours.	*High* External sensors could monitor any potential leakage.

Cathode Leakage (Closed Cell)	Release of water from cell	*Low* Gas connections are typically pressure tested before use and as such are suitability robust.	*Low* While there will be a drop in performance and in the case of PEM membranes the problem of drying out there is little risk to the user.	*Low* Minimal risk to user therefore needs no mitigation.
Cathode Leakage (Methanol)	Release of water and toxic methanol	*Medium* Any methanol that crosses the membrane and is not oxidised on the cathode catalysts will be exhausted.	*High* Release and build up of toxic vapours.	*High* External sensors could monitor any potential leakage.
Fire (Internal)	Fire starts within the cell housing	*Low* Construction materials are not flammable, however failure of the thermal management systems could result in over heating.	*High* The nafion membrane would release toxic chemicals on combustion.	*Medium* Operating temperature is typically tightly controlled and it is unlikely that thermal runaway would be allowed to occur.
Fire (External)	Fuel cell is set on fire either through misuse or accident	*Low* Entirely dependant on user	*High* The fuel container is likely to over pressurise and vent (if fitted with a bursting disk) leading to a jet of flame.	*Medium* Users must be made aware of the dangers and educated in how to avoid them.
Oxygen Depletion	Fuel cell is operated in a sealed or poorly ventilated room.	*Medium* The build up of exhaust CO_2 or depletion of oxygen may occur without air circulation.	*Low* For a portable application the levels of oxygen usage are equivalent to breathing.	*Low* Users must be made aware of the dangers and educated in how to avoid them.
Leak (Reformer)	Leak in or before fuel reformer	*Low* Gas fittings are typically pressure tested before use and as such are suitability robust.	*High* Leakage of toxic or flammable fumes (CO, methanol, fuel)	*Medium* External sensors could monitor any potential leakage.
Corrosion	Corrosion of internal systems	*Low* The favoured materials of construction are stainless steels and no corrosives are used.	*Variable* The severity depends on the location of corrosion.	*Low* Other components are likely to fail before significant levels of corrosion occur.

Table 15 - Risk Matrix for fuel cell powered devices

F ACKNOWLEDGEMENTS

The authors would like to thank the following individuals and organisations for their help -

QinetiQ - *Gary Mepsted, Robert Reeve*
Intelligent Energy - *Alison Cavey, Alison Harrison, Jon Moore, Philip Mitchell, Robert Boalch.*

Adelan
Alstom
Ballard
Ceramic Fuel Cells Limited
Ceres Power
Energy Research Centre of the Netherlands
European Fuel Cells Group
Global Thermoelectric Inc.
Imperial College of Science Technology and Medicine
Johnson Matthey
Rolls Royce
Siemens
Wellman Defence Ltd
Ztek

G REFERENCES

[1] G.J.K. Acres, *J. Power Sources*, **100** (2001) 60-66
[2] P. Costamagna, S. Srinivasan, *J. Power Sources*, **102** (2001) 242-252
[3] P. Costamagna, S. Srinivasan, *J. Power Sources*, **102** (2001) 253-269
[4] M. Hogarth, X. Glipa, "High Temperature Membranes For Solid Polymer Fuel Cells" DTI/Pub Urn 01/893 (2001)
[5] N.Q. Minh, *J. Am. Ceram. Soc.*, **76** (1993) 563-588
[6] B.C.H. Steele, *Solid State Ionics*, **134** (2000) 3-20
[7] Siemens Westinghouse - Power Generation (http://www.siemenswestinghouse.com/en/fuelcells/demo)
[8] N.F. Bessette, B.P. Borglum, H. Schichl, D.S. Schmidt, "Siemens SOFC Technology on the Way to Economic Competitiveness" *International Turbomachinery*, May/June 2000
[9] R. Reeve, "Update on Status of Direct Methanol Fuel Cells", DTI/Pub URN 02/592 (2002)
[10] Toshiba Press Release, reported on AsiaBizTech (www.nikkeibp.asiabiztech.com)
[11] www.smartfuelcell.com, Performance Data Sheet
[12] M.M. Mench, Z.H. Wang, K. Bhatia, C.Y. Wang, "Design of a Micro Direct Methanol Fuel Cell (μDMFC)", *Proceedings of the IMECE'01*, New York, November 11-16, 2001
[13] Tech News - CNET.com (news.com.com)
[14] M.M. Friedman, "A New Class of Electrocatalysts and a Gas Diffusion Electrode Based Thereon" (2001), Patent No. WO 01/15253 A1
[15] Defense Advanced Research Projects Agency - MEMS Programme (www.darpa.mil/mto/mems)
[16] Motorola Press Release, reported in *Fuel Cells Bulletin* 38 (2001) 4 & Environmental News Service (ens.lycos.com/renewables)
[17] www.herahydrogen.com
[18] www.powerball.net
[19] www.milleniumcell.com
[20] A. Chambers, C. Park, R.T.K. Baker, N.M. Rodriguez, *J. Phys. Chem. B*, **102 [22]** (1998) 4253
[21] B.K. Gupta, O.N. Srivastava, *Int. J. Hydrogen Energy* **26** (2001) 857
[22] P. Irving, W.L. Allen, Q. Ming, T. Healey, "Novel Catalytic Fuel Reforming with Advanced Membrane Technology" *Proceedings of the 2001 DoE Hydrogen Program Review*, NREL/CP-570-30535 (2001) (www.tekkie.com)
[23] E.A. Daymo, D.P. VaderWiel, S.P. Fitzgerald, Y. Wang, R.T. Rozmiarek, M.J. LaMont, A.Y. Tonkovich, "Microchannel Fuel Processing for Man Portable Power" (www.pnl.gov/microcats)
[24] E. Jones, J. Holladay, S. Perry, R. Orth, R. Rozmiarek, J. Hu, M. Phelps, C. Guzman, "Sub-Watt Power Using an Integrated Fuel Processor and Fuel Cell" (www.pnl.gov/microcats)
[25] K.F. Jensen, *Chemical Engineering Science*, **56** (2001) 293-303
[26] Frost & Sullivan, Euromonitor, BCC (www.frost.com)
[27] Power 2001: Smart Handheld Device Unit Sales - Forecast
[28] InfoTech Trends, 00Q1 (www.infotechtrends.com)

[29] "CMR Fuel Cells - Leading the way in fuel cell technology" (www.genericsgroup.com/fuelcell)
[30] S. Hill, "Cell-ers market - New fuel cell materials promise powerful future", *Materials World*, **10** [1] (2002) 12-14
[31] R.G. Hockaday, "Micro-Fuel Cell Devices", Patent No. US 6,326,097 B1 (2001)
[32] R.F. Savinell, "Fuel Cell Research and Development"(www.cwru.edu)
[33] C. Hebling, A. Heinzel, M. Müller, C. Müller, K. Tüber, A. Schmitz, "Fuel Cells for Low Power Applications: Construction, Simulation and Measurement" (www.ise.fhg.de)
[34] M. Kothare, www.lehigh.edu, article from Global Technology Scan (www.globaltechnoscan.com)
[35] M. Conte, A. Iacobazzi, M. Ronchetti, R. Vellone, *J. Power Sources*, **100** (2001) 171-187
[36] "Long Term Reductions In Greenhouse Gas Emissions In The UK", Report of an Inter-department Analysts Group (February 2002)
[37] UK Cabinet Office, "The Energy Review - A Performance And Innovation Unit Report", (February 2002)
[38] M. Pehnt, *Int. J. Hydrogen Energy*, 26 (2001) 91-101
[39] Department for Transport, Local Government and the Regions, "Powering Future Vehicles: Draft Government Strategy", December 2001 (www.roads.dtlr.gov.uk/vehicle/environment/futurepower)
[40] European Commission, Clean Urban Transport "The Civitas Initiative", (europa.eu.int/comm/energy_transport/en/cut_en/cut_civitas_en.html)
[41] G. Graham, A. Cruden, J. Hart, "Assessment of the Implementation Issues for Fuel Cells in Domestic and Small Scale Stationary Power Generation and CHP Applications", ETSU F/03/00235/00/00 (2002)
[42] Working Borough Council (www.woking.gov.uk)
[43] Reported in 'The Herald On-Line", (www.theherald.co.uk)
[44] European Directive on Waste Electrical and Electronic Equipment (WEEE)
[45] D. Hart, Presentation at Generation H, April 2002
[46] Department of Trade and Industry: Sustainable Energy Programme, (www.dti.gov.uk/renewable)
[47] D. Hart, R. Fouquet, A. Bauen, M. Leach, P. Pearson, D. Anderson, D. Hutchinson, "Methanol Supply and its Role in the Commercialisation of SPFC Vehicles", ESTU F/02/00142/REP (1999)
[48] "IEA Agreement on the Production and Utilization of Hydrogen, Task 12: Metal Hydrides and Carbon for Hydrogen Storage, Final Task Report 2001", ed. G. Sandrock (www.eren.doe.gov/hydrogen/iea/iea_task12.html)
[49] BMW World (www.bmwworld.com/models/750hl.html)
[50] Department of Trade and Industry: Advanced Fuel Cells Programme (www.h2net.org.uk/H2_support/DTI.htm)
[51] "Europe as a Global Player: The Contribution of Education and Research: Summary of the Discussion After the 2001 Zuckerman Lecture", The Foundation for Science and Technology, November 2001
[52] European Commission 5th Framework Programme (europa.eu.it/comm/researc/fp5.html)

[53] www.miljo.lth.se/Helby/USHER summary -.htm
[54] www.scottishfuelcellconsortium.org.uk
[55] www.wavegen.co.uk
[56] ETSU report, "Fuel Cells Niche Market Applications & Design Studies", ETSU F/03/00205/REP
[57] BTI Web site, "Small Format Battery Market", (www.bti.ca/actual.htm)
[58] Manhattan Scientifics, "Potential Fuel Cell Markets" (www.mhtx.com/technology/micro_fuel_cell/marketanal_a.htm)
[59] *Fuel Cell Catalyst*, Vol.1, No.3, Spring 2001.
[60] C.K. Dyer, Fuel Cells for Portable Applications
[61] H. Colell, M. Bronold, C. Leu, *Proceedings of Fuel Cell 2000*, Lucerne (2000), 19-28
[62] U. Bossel, *Proceedings of Fuel Cell 2000*, Lucerne (2000), 53-59
[63] M.Vazquez, A. Vegas, M. Buffin, D.U. Sauer, L. Daza, A. Guerrero, R. Ornelas, R. Liebig,, *Abstracts of the 2000 Fuel Cell Seminar*, Portland (2000), 807-810
[64] Internal presentation: "Air-Breathing PEM Fuel Cells – For Man Portable and Battery Replacement Applications" (www.ballard.com)
[65] R. Mosdale, S. Escribano, *Abstracts of the 2000 Fuel Cell Seminar*, Portland (2000), 440-443
[66] R.J. Novak, *Proceedings of the 7th Grove Fuel Cell Symposium*, London (2001) 6.4
[67] J.D. Morse, *Proceedings of the Knowledge Foundation's 4th Annual International Symposium*, Washington (2002)
[68] M. Brocco, S. Santomassimo, M. Stefanoni, *Proceedings of the 1st European PEFC Forum*, Lucerne (2001), 547-553
[69] L.Cardinali, *Proceedings of the 7th Grove Fuel Cell Symposium*, London (2001) 5.8
[70] S.C. Yen, N.Y. Sheu, *Abstracts of the 2000 Fuel Cell Seminar*, Portland (2000) 79-82
[71] Y.C. Cheng, C.L. Lin, C.P. Chu, T.P. Perng, *Abstracts of the 1998 Fuel Cell Seminar*, Palm Springs (1998) 659-662
[72] A. Heinzel, M. Zedda, R. Nolte, T. Meyer, H. Schmidt, *Abstracts of the 1998 Fuel Cell Seminar*, Palm Springs (1998) 686-688
[73] C.S. Kim, T.H. Yang, D.H. Peck, S.H. Choi, *Abstracts of the 2000 Fuel Cell Seminar*, Portland (2000), 424-427
[74] A. Dickman, D. Edlund, C. Dearing, *Abstracts of the 2000 Fuel Cell Seminar*, Portland (2000), 395
[75] R.J. Kelly, "Portable Fuel Cell Power Supply", Patent No. US 6,268,077 B1 (2001)
[76] P. Osenar, Proceedings of the Knowledge Foundation's 4th Annual International Symposium, Washington (2002)
[77] L.P. Jarvis, T.B. Atwater, E.J. Plichta, P.J. Cygan, *Journal Of Power Sources*, **70** (1998) 253-257
[78] L.P. Jarvis, T.B. Atwater, P.J. Cygan, *Journal Of Power Sources*, **79** (1999) 60-63
[79] J. Roser, G. Zettisch, J. Scholta, L. Jorissen, J. Garche, *Proceedings of Fuel Cell 2000*, Lucerne (2000), 75-83