PERGAMON

International Journal of Hydrogen Energy 27 (2002) 507–526

International Journal of HYDROGEN ENERGY

www.elsevier.com/locate/ijhydene

An assessment of alkaline fuel cell technology

G.F. McLean *, T. Niet, S. Prince-Richard, N. Djilali

University of Victoria, POB 3055, STN CSC Victoria, BC Canada V8W 3P6

Abstract

This paper provides a review of the state of the art of alkaline fuel cell (AFC) technology based on publications during the past twenty-five years. Although popular in the 1970s and 1980s, the AFC has fallen out of favour with the technical community in the light of the rapid development of Proton Exchange Membrane Fuel Cells (PEMFCs). AFCs have been shown to provide high power densities and achieve long lifetimes in certain applications, and appear to compete favourably with ambient air PEM fuel cells. In this report we examine the overall technology of AFCs, and review published claims about power density and lifetime performance. Issues surrounding the sensitivity of the AFC to CO_2 in the oxidant stream are reviewed and potential solutions discussed. A rough cost comparison between ambient air AFCs and PEMFCs is presented. Overall, it appears the Alkaline Fuel Cell continues to have potential to succeed in certain market niche applications, but tends to lack the R& D support required to refine the technology into successful market offerings. © 2002 Published by Elsevier Science Ltd on behalf of the International Association for Hydrogen Energy.

1. Introduction

The alkaline fuel cell (AFC) was the first fuel cell technology to be put into practical service and make the generation of electricity from hydrogen feasible. Starting with applications in space the alkaline cell provided high-energy conversion efficiency with no moving parts and high reliability. AFCs were used as the basis for the first experiments with vehicular applications of fuel cells, starting with a farm tractor in the late 1950s equipped with an Allis Chalmers AFC (Kordesch and Simader, 1996). This was followed by the now famous Austin A40 operated by Karl Kordesch in the early 1970s [1] and continuing today with the commercialization activities of the ZEVCO company [2,3]. However, despite its early success and leadership role in fuel cell technology, AFCs have fallen out of favour with the research community and have been eclipsed by the rapid development of the Proton Exchange Membrane fuel cell (PEMFC) as the technology of choice for vehicular applications.

This paper provides a critical overview of the state of the art of AFC technology and attempts to synthesize the published information on AFCs to provide a unified view of the technology. A re-examination of the economics of AFC technology is also presented. The issues generally assumed to have caused the demise of interest in AFCs, namely low power density and electrolyte poisoning are addressed in detail to provide as complete a picture as possible, based primarily on published and publicly available information.

The PEM fuel cell has recently emerged as the technology of choice for low temperature, moderate power applications and has largely displaced the AFC in this application. Because of this, we have provided a comparison between alkaline and PEM technology wherever possible. In particular, a detailed cost comparison between PEM and AFCs is included.

The public domain literature has been reviewed including the most recently published results on alkaline electrode materials and manufacture as well as older publications describing the state of the art around 1980. Earlier publications, which largely describe the now defunct space applications of AFC technology, have not been reviewed. The overall purpose of this review has been to establish a technical opinion about the viability of AFCs and to identify key areas for research.

The report is structured as follows. In Section 2 we provide a general orientation to AFC technology and review the nature of the published research and recent corporate

---

* Corresponding author. Fax: +250-721-6323.
E-mail address: gmclean@me.uvic.ca (G.F. McLean).

0360-3199/02/$20.00 © 2002 Published by Elsevier Science Ltd on behalf of the International Association for Hydrogen Energy.
PII: S0360-3199(01)00181-1

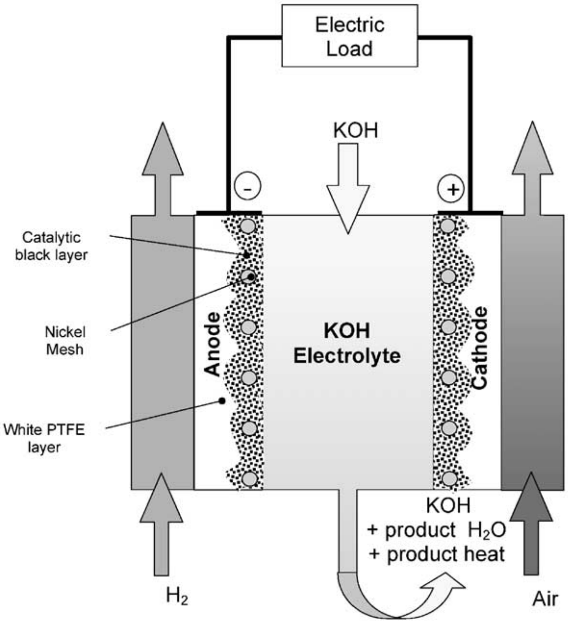

Fig. 1. Alkaline fuel cell composition.

activities. In Section 3 we discuss the major technical issues confronting AFCs, including the reported power densities, poisoning issues, lifetime, duty cycles and systems considerations. This section also provides a hint at some new AFC technologies that may be of interest. Section 4 provides a detailed cost analysis and includes a comparison to published PEM cost projections. In Section 5 we provide conclusions and state our general technical position.

2. Alkaline fuel cell background and development status

2.1. Principle of operation

AFCs use an aqueous solution of potassium hydroxide as the electrolyte, with typical concentrations of about 30%. The overall chemical reactions are given by

Anode reaction	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$
Cathode reaction	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Overall cell reaction	$2H_2 + O_2 \rightarrow 2H_2O$ +electric energy + heat

By-product water and heat have to be removed. This is usually achieved by recirculating the electrolyte and using it as the coolant liquid, while water is removed by evaporation. A schematic of the recirculating electrolyte AFC is shown in Fig. 1 (after De Geeter [4]).

The electrodes consist of a double layer structure: an active electrocatalyst layer, and a hydrophobic layer. According to the dry manufacturing method described by Kivisaari et al. [5] and De Geeter [4], the active layer consists of an organic mixture (carbon black, catalyst and PTFE) which is ground, and then rolled at room temperature to cross link the powder to form a self supporting sheet. The hydrophobic layer, which prevents the electrolyte from leaking into the reactant gas flow channels and ensures diffusion of the gases to the reaction site, is made by rolling a porous organic layer, again to cross-link the layer and form a self-supporting sheet. The two layers are then pressed onto a conducting metal mesh. The process is eventually completed by sintering. The total electrode thickness is of the order of 0.2–0.5 mm.

A major operating constraint is the requirement for low carbon dioxide concentrations in the feed oxidant stream. In the presence of CO_2, carbonates form and precipitate;

$$CO_2 + 2OH^- \rightarrow (CO_3)^{2-} + H_2O.$$

The carbonates can lead to potential blockage of the electrolyte pathways and/or electrode pores. This issue is discussed in detail in Section 3.2.1.

The inherently faster kinetics of the oxygen reduction reaction in an alkaline cell allows the use of non-noble metal electrocatalysts. It is useful to compare the eletrochemical performance of AFCs and PEMFCs in terms of the relationship between cell potential, E, and current density, i. When mass transport limitations are negligible (low to intermediate current density), E and i are approximately related by Blomen and Mugerwa [6]

$$E = E_0 - \beta \log i - Ri$$

with

$$E_0 = E_r + \beta \log i_0,$$

where, E_r is the reversible thermodynamic potential, β and i_0 are the Tafel slope and the exchange current density for the oxygen reaction, and R is the differential resistance of the cell.

Differentiating Eq. (1) provides further insight into the relative importance of losses associated with electrode kinetics and electric resistance:

$$\frac{\partial E}{\partial i} = -\frac{\beta}{i} - R.$$

At low current densities, the first term on the RHS is dominant and corresponds to the typical steep fall of the cell potential with increasing current. At higher current densities, $\beta \ll R$ and the second term becomes dominant, resulting in a quasi-linear drop of cell potential with current, until mass transport limitations become important. Optimal performance is obtained for low Tafel slopes (β) and cell resistance (R), and high exchange current density (i_0). The better electrode kinetics of AFCs results in Tafel slopes lower by about 30% than for PEMFC, when Pt is used as a catalyst in both [7].

The main contribution to cell resistance is due to the ionic/protonic resistivity of the electrolyte. Again AFCs appear to have lower electrolyte resistivities (0.05 vs. 0.08 Ω/cm^2 for PEMFC). It should be pointed out that new generation ultra thin acidic polymer membranes [8] achieve low resistance. Nonetheless AFCs have an intrinsic advantage over PEMFC on both cathode kinetics and ohmic polarization. A puzzling aspect of all published AFC data is that polarization curves are invariably presented for maximum current densities of about 400 $\mathrm{mA/cm}^2$, with no indication that mass transport limitations have been reached. A possible explanation is that, for cost reasons, the catalysts of choice are nickel alloys. Nickel is, however, susceptible to oxidation, leading to high performance degradation over time. This problem would presumably be exacerbated at higher current densities.

2.2. *Research activity level*

The strongest and most consistent advocate for AFC research has been Professor Kordesch, who has been researching, developing and promoting this technology for over 30 years and who continues to be involved in its commercialization. Kordesch gained notoriety for his development of a fuel cell powered Austin A40 car in the early 1970s [1] and his accounts of the experience gained with that test platform and fuel cell stack have formed the core of his publications ever since [1,9–13].

The work of Kordesch links directly into the commercially driven research of the Elenco/Zevco companies. The vast majority of the publications presenting system design or performance information is produced either directly by ZEVCO researchers, or is based on ZEVCO AFC modules [2,4,14–17]. This makes it difficult to separate potential AFC system performance from Zevco system performance.

During the early 1990s Olle Lindstrom published several excellent reviews of fuel cell technology in general, and AFC in particular [18–20]. However, his recent death prevents the possibility of using him as an arms length expert for the purpose of qualifying the ZEVCO claims.

The remainder of the published research on AFC technology consists largely of detailed studies of component parts of AFCs, conducted by individual researchers. The work is dominated by detailed characterization, analyses and evaluations of components, mostly electrodes. Information on AFC *systems* is scarce. Research publications of this type continue to be published at a roughly constant rate. Lindstrom's 1993 review of the state of the art of fuel cell technology revealed that 10% of publications over the 10-year period from 1983 to 1993 were associated with AFCs.

2.3. *Corporate activities*

Corporate development activities have been shifting away from AFCs and more towards PEM for low temperature and mobile fuel cell applications since the mid 1980s. Major European projects conducted by Siemens, Hoechts and DLR were all cancelled prior to 1996 [21]. North American development of AFCs for space applications is continued by United Technologies/International fuel Cells. However, this work appears to be limited to providing fuel cells to the space shuttle program and appears to have no aspirations for entering other markets [22].

The remaining developers of AFC technology are almost exclusively related to Zetek Corporation. Zetek is the parent organization of three companies involved in developing products for transportation (Zevco plc), marine (ZeMar Ltd) and stationary power (ZeGen Ltd) applications. Recent developments from Zetek include the announcement of a new 5MW automated production line in Germany that will see Zetek manufacture more fuel cells than the combined production capacity of the rest of the world [23].

Astris Energi [24] recently announced a 4-kW prototype systems and offer the only off the shelf commercial source of low power AFCs. The Electric Auto Corporation is working with the Technical University of Graz (with Kordesch) to develop a lead-cobalt battery/AFC hybrid vehicle [25]. These two initiatives are small compared to the magnitude of Zetek's activities.

3. Technical review

3.1. *Power density*

Fuel cell systems have typically been evaluated on the basis of their volumetric and gravimetric power density, probably due to the historical challenge posed by developing a fuel cell system of adequate power within the volume and weight constraints imposed by equivalent power internal combustion engines. Such measures of evaluation must be based on overall system volume or weight, thus making it difficult to assess power density on the basis of the narrowly defined performance of the fuel cell electrochemical reaction. In the absence of absolute volumetric or gravimetric system power densities, polarization information is often used to assess the merits of particular fuel cell designs. This approach is reasonable in providing a figure of relative merit as a cell with higher current density, at an equivalent voltage, will provide higher overall power density so long as the stack geometry and ancillary systems remain constant, which is a reasonable assumption for the majority of PEM and AFCs. Therefore, in either case it is possible to judge the relative merits of fuel cells.

In half-cell testing particular components of the fuel cell are evaluated with potentials measured against some reference electrode. Direct comparison between different experimental results becomes difficult to assess in these situations because the full details of the experiments are not provided, different reference electrodes are used, or different test conditions employed.

The foregoing discussion serves to point out the difficulty encountered in trying to assess the power densities reported by AFC researchers. Results are often incomplete, and very few reported results discuss *system* performance. Nonetheless, we can review the partial results that have been reported and infer from them a reasonable picture of the power density achieved by AFCs.

3.1.1. Space applications

The AFC was initially used in space applications to produce electrical power for mission critical services. As such, these fuel cells were designed to provide reliable power, with low volume and weight, at virtually unconstrained cost.

A matrix type alkaline H_2–O_2 fuel cell is discussed by Matryonin et al. [26]. The cell is indicated as operating at 100°C and pressures of 4–4.5×10^5 Pa. The presentation discusses the effects of varying these operating parameters on system performance. The performance is impressive, showing 3.2 A/cm^2 at 600 mV. The reported results show very good current density at high voltages with pressures between 30 and 60 psig.

Martin and Manzo [27] present performance data from the Orbiter fuel cell which is even more impressive. Operating with gas pressures of 200 psi and temperatures of 300 F and a 50% weight KOH electrolyte solution they report current densities up to 9 A/cm^2 at just over 0.7 V. Further information on the Orbiter fuel cell and the Siemens BZA4 is provided by Jo and Yi [28]. Their Orbiter data reports 1000 mA/cm^2 at 900 mV. The performance of the Siemens fuel cell indicates 1 A/cm^2 at 0.74 V. The orbiter cell is reported at an operating pressure of 60 psig compared to 30 psig for the Siemens cell.

Although these reported results for space based AFCs do not typically provide complete polarization curves, they nonetheless indicate very high current densities. It is important to remember that most of these results were obtained in the early 1970s or with 1970s technologies, well before today's highly optimized PEM systems had even been thought of. The available performance information from these space-based approaches is shown in Table 1.

3.1.2. Atmospheric pressure cells

The second distinct class of AFCs is based on operation at atmospheric pressure. This is the type of cell being developed commercially today, so these data are perhaps most relevant in validating any claims made by contemporary fuel cell manufacturers.

The oldest published results can be found in Binder et al. [29] which provides a summary of the state of the art of the AFC at that time. Current densities of 100 mA/cm^2 are reported there.

The most recently published ZEVCO performance [4] indicates normal operation at 100 mA/cm^2 range at 0.67 V per cell. Operation at current densities between 200 and 400 mA/cm^2 is discussed briefly, but no voltage information is provided. Kordesch et al. [12] discuss system performance, but like De Geeter do not provide a complete description of the operating parameters used in the system. Even so, current densities of 250 mA/cm^2 are reported. Similar performance is apparently achieved with Platinum, Silver or a low cost Spinel catalyst. Weight and volume information is provided for the original Kordesch Austin fuel cell vehicle [10], but these data are now over 30 years old. Zevco's more recent designs easily supersede the original Kordesch system. Summary results with an Elenco stack are reported in Vegas et al. [14]. The reported data indicate very low current densities of only 50 mA/cm^2.

The systems discussed in the preceding paragraph are based on unipolar cell construction. Performance of a bipolar plate AFC are reported in Tomantschger et al. [30] where current density similar to De Geeter is presented, i.e. 100 mA/cm^2 at 0.85 V running on air. The cell voltage increased to 0.9 V when pure oxygen was used.

Performance of an AFC using a solid ionomer alkaline membrane is reported in Swette et al. [31]. The system was operated at 44 psi gas pressures at 40°C, which is a unique operating point. Using a Platinum–Irridium catalyst produced the best results, but still only 100 mA/cm^2 was produced at 800 mV. The solid ionomer alkaline membrane is intriguing because it suggests one possible path for developing AFC systems combining the desirable properties of a solid electrolyte with the fast anode reaction kinetics of an alkaline cell. Unfortunately, no further developments achieved with this technology have been published, leading us to conclude that the work has been discontinued.

An AFC stack developed specifically for operation with Biomass produced hydrogen is reported by Kiros et al. [32]. Both H_2–air and H_2–O_2 performance were reported, but the operating data were incomplete with no gas pressure information being provided. Performance of two generations of the design indicates 88/125 and 157/186 mA/cm^2 for air and O_2, respectively. Given the range of these performance values, we assume that atmospheric pressures are used.

Taken together, the atmospheric AFC performance results reported in the literature suggest that power densities between 100 and 200 mA/cm^2 have been achieved for several decades. The performance results are summarized in Table 2.

3.1.3. Performance of components

There have been numerous publications describing the performance of specific components of AFC systems, notably electrodes, where the object of the research has been to develop some incremental improvement over the state of the art. The results reported for such investigations tend to consist of half-cell reactions reporting current densities at different cell overpotentials with respect to a mercury or silver reference electrode. Generally these investigations do not provide useful performance data, but rather indicate the

Table 1
Summary of space application AFC performance

Operating point		Power (W/cm^2)	Press. (psig)	Temp. (°C)	Source
mV	mA/cm^2				
950	140	0.133	29	98	[26]
950	220	0.209	58	98	[26]
950	310	0.2945	116	98	[26]
950	150	0.1425	58	65	[26]
950	280	0.266	58	96	[26]
950	440	0.418	58	130	[26]
600	3200	1.92	58	98	[26]
600	4200	2.52	58	121	[26]
800	6730	5.384	299	149	[27]
740	1000	0.74	29	80	[28]
900	320	0.288	29	80	[28]
900	1000	0.9	60	80	[28]

Table 2
Summary of terrestrial application AFC performance

Current density 0.7 V (mA/cm^2)	Power at 0.7 V (W/cm^2)	Point 2		Power at Point 2 (W/cm^2)	Press. (psig) & gases	Temp. (°C)	Source
		mV	mA/cm^2				
290	0.203	800	260	0.208	atm H_2–air	75	[12]
450	0.315	800	280	0.224	atm H_2–air	75	[12]
N/A	N/A	670	100	0.067	atm		[4]
90	0.063	800	35	0.028	44 H_2–air	40	[31]
108	0.076	800	102	0.082	44 H_2–air	40	[31]
115	0.081	570	225	0.128	atm H_2–air	40?	[32]
125	0.088	700	125	0.088	atm H_2–O_2	40	[32]
88	0.062	700	88	0.062	atm H_2–air	40	[32]
N/A	N/A	750	186	0.140	atm H_2–O_2	40	[32]
157	0.110	700	157	0.110	atm H_2–air	40	[32]
N/A	N/A	850	100	0.085	atm H_2–air	65	[30]
N/A	N/A	900	100	0.090	atm H_2–O_2	65	[30]
87	0.061	670	100	0.067	atm H_2–air	70	[2]
40	0.028	N/A	N/A	N/A	atm H_2–air	60	[14]

extent of work being undertaken to refine and optimize the performance of AFC systems.

3.1.3.1. Three-dimensional electrodes. Several reports have presented the idea of using a fluidized bed electrode structure in which a bed of electrode particles mixed with liquid electrolyte is subject to reactant gas flow *through* the bed. The fluidized bed is thus formed from the electrode particle, electrolyte, gas mix. A coarse membrane separates the anode and cathode reactions and electrodes are inserted into the fluidized beds to gather current.

A co-axial cylindrical single cell described in Nakagawa et al. [33] produced > 1 A at 0.8 V. The volume of this single cell was not reported. In Matsuno et al. [34,35] the design and performance of an alternative structure for fluidized bed electrodes is described. Operation of an AFC using a flooded gas diffusion electrode is reported in Holeschovsky et al. [36]. Only half-cell results were reported here, with the promise of a forthcoming article describing the performance of a practical system based on this idea. No such paper has been found.

Most conventional AFC designs devise methods to contain the liquid electrolyte, creating a system with operational features resembling those of solid membrane cells. By contrast, this approach uses the fluid properties of the electrolyte to eliminate the need for construction of gas diffusion electrodes completely. Although performance is still correlated to the surface area of the triple interface, this area is now contained within the volume of the fluidized bed. There is thus potential for very high power densities in a very low cost package. We are also tempted to speculate that issues surrounding electrode poisoning due to formation of carbonates may be far less serious in this design due to the elimination of the porous gas diffusion electrode.

The fluidized bed approach to AFC design represents a completely new direction for fuel cell technology development that is a direct consequence of the liquid electrolyte utilized in AFCs. Although the preliminary results we have seen with fluidized bed AFCs are not impressive, this technology is worth watching.

3.1.3.2. Electrode materials. Research continues in the development of electrode materials to improve alkaline cell performance. Baseline performance of Nickel electrodes is described in Al Saleh et al. [37,38] which is then improved upon through the impregnation of copper into the Nickel electrode [39] with the improvement being attributed to reduced contact resistance due to the copper. Introduction of Tin into a Nickel cathode is shown to reduce Hydrogen overpotential [40]. Performance of Silver catalyst is compared to Platinum in Lee et al. [41] with the conclusion that the two perform equivalently producing up to 200 $\mathrm{mA/cm^2}$ at 0.8 V. Electrodes based on Raney Silver are reported in Gultekin et al. [42] but with no useful power or current density information reported. Commercial electrodes are reported to provide similar current densities [43]. These reports show the steady performance improvement in electrode performance but do not introduce any radically new insights or technologies.

3.1.3.3. Electrode fabrication methods. The manner of production of electrodes for AFCs has significant impact on the performance of the overall cell. In general, the electrodes are manufactured by a method of wet fabrication followed by sintering or by a method of dry fabrication through rolling and pressing components into the electrode structure. In all cases the resulting electrode consists of a hydrophobic catalyzed layer on top of a gas porous conductive layer which is in turn bonded to a porous backing material that is usually metallic. The best results appear to be achieved when the electrode structure is built up from several layers and most of the current literature describes two-layer fabrication techniques.

A good overall description of the alternative methods of electrode fabrication is provided in Kivisaari et al. [5]. In seeking an optimal air electrode structure some 30 or so different electrodes were developed and tested. The best results showed half-cell results with current densities of 500 $\mathrm{mA/cm^2}$ and no tendency to reaching current limits.

The effect of platinum loading on a multi-layer rolled electrode is reported in Han et al. [44]. 125 $\mathrm{mA/cm^2}$ is reported with 0.3 $\mathrm{mg/cm^2}$ of platinum catalyst. The current density increases to 225 $\mathrm{mA/cm^2}$ when the platinum loading was increased to 2.0 $\mathrm{mg/cm^2}$.

Alternatives to the basic fabrication techniques have been reported, but the results do not seem to suggest any great improvements in performance. Composite electrodes with carbon fibers pressed into a metal backing are reported in Ahn [45]. Use of an Oxygen Plasma treatment to increase the surface area of carbon black on a metallic substrate is reported in Li and Horita [46]. No clear performance improvement is reported in either case. A filtration method combining the best features of wet and dry fabrication is presented in Sleem et al. [47] with performance roughly equivalent to other AFCs (current densities approximately 180 $\mathrm{mA/cm^2}$).

The volumetric and gravimetric power density of the ZEVCO module is reported to be on the order of 0.09 kW/kg and 0.06 kW/l, respectively [2]. It is conceivable that these densities could be doubled if current densities can be increased. However, there do not appear to be any huge breakthroughs on the horizon (either at ZEVCO or elsewhere) that would vastly improve the power density of the systems. The most promising area, perhaps, is in the fluidized bed electrode structures. This research, however, is a long way from producing commercial products.

3.1.4. Comparison to PEM

Typical PEM fuel cell performance describes a system in which current densities are greater than 1 $\mathrm{A/cm^2}$ at 0.6 V or higher, volumetric densities exceed 1 kW/l and gravimetric densities exceed 1 kW/kg. However, caution must be used when applying these rough numbers as a measure of fuel cell system performance.

There is no doubt that PEM fuel cell technology is now producing power densities well in excess of the performance reported for ambient AFC technology. However, the PEM systems are typically pressurized to at least 30 psig. In pressurized AFC systems similar or even higher power densities were reported many years ago. Rather than optimizing these high power technologies and driving price down through volume manufacturing the AFC community has evolved toward lower power ambient air systems. Therefore PEM and AFC *systems* are fundamentally different.

Published results for ambient air operated PEM systems suggest performance that is on the same order of magnitude as ambient air alkaline systems. Kordesch and Simader [48] provide comparative information between ambient air and pressurized operation of an undisclosed PEM fuel cell using a Dow membrane. Sugawara et al. [49] provide polarization information for a 40 cell ambient air PEM system and Koschany [50] presents polarization information for a small air-breathing cell designed to power cellular phones. The current density achieved at 0.7 and 0.6 V for each case is presented in Table 3. Note that these data are gathered from available literature and do not necessarily reflect state of the art performance of ambient air PEM systems.

Table 3
Summary of ambient air PEM fuel cell performance

Current density 0.7 V (mA/cm^2)	Power at 0.7 V (W/cm^2)	Current density 0.6 V (mA/cm^2)	Power at 0.6 V (W/cm^2)	Source
200	0.140	425	0.255	[50]
250	0.175	500	0.300	[48]
125	0.088	450	0.270	[49]

Comparing the results presented in Tables 2 and 3, it is apparent that available alkaline and PEM technologies achieve roughly equivalent current densities when operated on ambient air oxidant streams. This means that in applications where ambient air alkaline technology is proposed (as in Zevco's planned hybrid vehicle system) there is no reason to think that the alkaline technology will be easily displaced by a better, more efficient PEM system.

3.2. *Poisoning and contamination issues*

AFCs, like all fuel cells, have limits to the amount of impurities they can tolerate in their feed gas streams. The "poisoning" of the fuel cell by impurities can be caused by any number of different gases. In published reports, carbon dioxide contained in the oxidant stream has received the most attention, since it is perceived as the only major issue preventing the commercialization of terrestrial AFCs running with air. No information on other impurities in the oxidant stream has been mentioned. The effect of carbon dioxide, as well as carbon monoxide and oxygen, on the anode side of an AFC has also been studied.

3.2.1. *Effect of carbon dioxide on the cathode*

The common perception of the AFC is that they cannot operate if there is any carbon dioxide in the cathode feed gas streams. Since terrestrial application AFCs will in all likelihood operate on ambient air, this is a significant issue.

It is suspected [37,38,48] that the poisoning reaction involves the alkaline electrolyte directly by the following reaction(s):

$$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O \quad \text{and/or}$$
$$CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O.$$

This has the effect of reducing the number of hydroxyl ions available and therefore reducing the ionic conductivity of the electrolyte solution. It may also have the effect of blocking the pores in the electrodes. The carbonate "may precipitate and block the micro pores of the Raney catalyst or may stay as a liquid and reduce the ionic conductivity of the electrolyte" [37,38]. Kordesch states that the carbon dioxide reduces electrode "breathing" [9]. As well as these bulk effects, the effect on water management due to a change in vapor pressure and/or a change in electrolyte volume can be detrimental [51].

A number of papers present a point blank dismissal of this problem, as illustrated by the following quote: "it is often reported that the AFC ... must be fed with pure oxygen because it is poisoned by CO_2 in the atmosphere ... None of these myths can be substantiated" [4,15]. However, these papers present no data to substantiate their claim.

Al Saleh et al. [37] showed that concentrations of up to 1% CO_2 in the oxidant stream of Ag/PTFE electrode at 72°C did not significantly affect the cell performance over a period of 200 h. However, at 25°C the CO_2 did adversely affect the performance. It is thought that the solubility of K_2CO_3 is lower at 25°C and therefore precipitates out and blocks the electrode pores. Al-Saleh et al. verified the presence of precipitated K_2CO_3 in the electrodes for the 25°C run using X-ray diffraction, thereby proving that the electrodes were directly affected in this experiment.

The presence of K_2CO_3 in the electrolyte by itself does not appear to produce any degradation in performance over the course of a 48-h period. Al-Saleh et al. showed this by mixing K_2CO_3 into the electrolyte and observing the current supplied at a specific over potential for 48 hours. In this test, the K_2CO_3 did not penetrate the pores of the electrodes or degrade the performance.

Appleby and Foulkes [51] discuss the fact that improved electrode formulations and structures can give dramatically varied results. Gulzow [21], in investigations with DLR, developed this concept and found that the effect of CO_2 on the electrodes was minimal if the electrodes were properly constructed. Gulzow used silver electrodes, which do not show the same fine pore structure as the standard Raney-nickel electrodes used in most AFC systems. This ensured that the carbonates did not block the pore structure and allowed the cells to work much more effectively. Gulzow found a 17 μV/h degradation for all cases, with and without carbon dioxide in the feed gas streams.

Gulzow [21] also discussed the changing of the electrolyte every 800 h. This ensured that the carbonates did not precipitate out of the electrolyte solution and damage the electrodes while also maintaining the electrolyte concentrations. In another paper, Gulzow [66] discusses the addition of water to the electrolyte to maintain the hydroxyl ion concentration.

Van Den Broek et al. [16] states that "feeding a module over 6000 operating hours with CO_2-free air and with air containing 50 ppm CO_2, respectively, did not show any difference in performance or endurance". This may imply that the poisoning mechanism is not entirely CO_2 based and that other effects may be taking place. This is supported by Kinoshita [52] who discusses other effects including the oxidation of the carbon electrode to produce carbon dioxide and, consequently, carbonates. Kinoshita suggests that a highly active catalyst, although allowing for higher potentials, will cause a more rapid oxidation of the carbon electrodes.

Michael [2] reported that at 670 mV with 50 ppm CO_2 in the air stream over 6000 h the power output was reduced from 70 to 50 $\mathrm{mW/cm^2}$ (approximately a 30% reduction) for a 500 W stack. The paper stated that this was a non-continuous test but did not provide information on electrolyte replenishment or replacement.

A test with intermittent operation was also performed by Zevco [2]. They found that the decrease in performance over time was greater with intermittent operation than with continuous operation. However, the draining of the electrolyte when the cells were shutdown seemed to prevent a large part of this deterioration. This seems to imply corrosion of the electrode materials by the electrolyte and not necessarily a CO_2 poisoning effect. Kordesch [9] has also discussed this effect and discusses that the cells do not seem to degrade at all if draining and purging are employed.

3.2.2. Carbon dioxide strategies for the cathode

From the above discussion, it is evident that there is a carbon dioxide poisoning issue. A number of papers mention methods for dealing with this problem.

Kordesch and Simader [48] mention that the "Removal of the 0.03% carbon dioxide from the air can be accomplished by chemical absorption in a tower filled with, e.g., soda lime". One kilogram of soda lime has the ability to clean 1000 m^3 of air from 0.03% to 0.001% CO_2 [51]. Zevco, who use soda lime, typically use 1 kg of limestone per 8 kW h of operation in present testing [2]. However, this corresponds to only 7% of the limestone being reacted and Zevco believes that efficiencies up to 80% may be achievable by proper selection of column conditions and grain size [2]. If this efficiency is achieved, over 90 kW h of cleaned air could be produced from 1 kg of limestone. The numbers given by Appleby and Foulkes [51] indicate 135–250 kW h per kilogram of limestone at 20–30% oxygen utilization.

Regenerable absorbers using molecular sieves can easily achieve the reduction of atmospheric carbon dioxide to acceptable levels [51]. The requirement for dry air for these processes, since water is preferentially absorbed, and the cost of regeneration of these systems increases both their capital and operating costs. However, they can be used for both reformed gases on the anode side and for air on the cathode side.

The concept of electrochemical removal of the carbonates from the electrolyte is very interesting. By drawing a large current out of an AFC, the concentration of hydroxyl ions is reduced at the anode. At the same time, the carbonate ions migrate towards the anode. An acidic solution at the anode is produced with hydrogen carbonate being the major component. When the current density is increased further, a number of cascading effects occur with the end result being the electrolyzing of the carbonates out of the solution at the anode by the following reaction [51]:

$$H_2CO_3 \rightarrow H_2O + CO_2.$$

With a regeneration period where the cells are run at a higher current density performed at 7000 and 15,000 h, the lifetime of a cell was doubled to 20,000 h [51]. No reference is given to substantiate this claim. Pratt and Whitney developed a system, which incorporated special regeneration cells into a regular fuel cell stack, regenerating the electrolyte continuously for the stack running on air. They found that the loss of efficiency was less than 1% from the incorporation of these cells and that the cells could run with 3000–4000 ppm carbon dioxide without a serious effect [51].

One alternate strategy for CO_2 management involves the synergistic possibility of using liquid hydrogen to condense the carbon dioxide out of the air. Ahuja and Green [53,54] discuss this at length and develop a model for the heat exchanger required for this. Liquid hydrogen is a strong fuel candidate for fuel cells, especially in Germany, where there is a large amount of research being performed, and in situations where there are captive fleets of vehicles. This system would enable the recovery of the energy of cold, which is around 30% of the total energy available from liquid hydrogen.

There are two technologies that alleviate carbon dioxide poisoning. Fyke [55] discusses the possibility of a solid ionomer alkaline membrane that would enable a cell to run without the possibility of carbon dioxide poisoning, as there would be no free potassium cations to which the carbonate anions could attach. This is an intriguing concept but no progress in solid ionomer alkaline membranes has been reported since Swette et al. [31] discussed this possibility for regenerative fuel cells.

There are a number of possibilities involving the modification of the fuel cell operating parameters. Operating the electrodes at higher temperatures would increase the solubility of the K_2CO_3 in the electrolyte and prevent it from precipitating out [52]. As well, the circulating of the electrolyte improves the AFC tolerance to carbon dioxide significantly [12]. In general, modification of the operating conditions can prolong electrode life, but it is clear that the life expectancy of air cathodes is lower when CO_2 is present in the fuel cell [52].

3.2.3. Effect of impurities on the anode

Published information discusses the effect of carbon dioxide, carbon monoxide (CO) and oxygen on the anode. Al-Saleh et al. [37] tested the effect of CO_2 in the anode gas stream. They found that, although the presence of the

CO_2 adversely affected the performance, the effect was entirely reversible under all experimental conditions. No details were given regarding the process used to determine the reversibility, but it seems that the cell was tested with and without CO_2 a number of times in a cyclic manner. At 40 mA/cm^2 they found a 75 mV polarization effect between 0% and 4% CO_2 in the hydrogen stream.

The effect of CO in the anode gases of an AFC is, intriguingly enough, often reversible. At temperatures above $72^\circ C$, this effect was completely reversible and below this temperature it was at least partially reversible [56]. This effect was also found to be a specific polarization loss and did not seem to cause a continual loss over time.

Kiros [57] found that both CO and Oxygen in the anode gases significantly affected the polarization of an AFC at $55^\circ C$ in 6 M KOH due to a change in the surface properties of the electrode. No information on the reversibility of the effect was given in the conference abstract.

3.2.4. *Strategies for the anode*

The use of reformed fuels as the anode gases for AFCs has mostly been discounted. Kordesch suggests that the removal of the CO_2 from the feed gases would be very expensive and impractical, particularly for small systems [10,11]. It is therefore usually assumed that high purity hydrogen, either liquefied or compressed, will be used with AFC systems. Michael [2] also mentions this and states that the successful development of economic palladium membranes or molecular sieves might allow the AFC to use reformed hydrocarbon fuels.

3.2.5. *Summary of contamination effects*

CO_2 in the oxidant stream has a distinct effect on the performance of AFC systems even though questions remain about the exact cause. There is strong evidence that a large amount of this poisoning is reversible and that effective electrolyte management will mitigate a large part of the problem. This could be done in a similar manner as an oil change is performed on vehicles today.

The only method currently employed to alleviate the oxidant side carbon dioxide poisoning is CO_2 scrubbing using soda lime. Technically, this system works, but is not a strong option for commercial systems. This suggests that significant benefits could be obtained from the use of other scrubbing techniques.

3.3. *System issues*

The majority of published descriptions of AFC systems are based on the early work of Kordesch, followed by descriptions of Elenco [16,58] and then ZEVCO [4,12–14,30] systems. Complete lab scale systems are described in Khalidi et al. [59] and Ergul [60]. These do not provide descriptions of practical fuel cell stacks, but do provide alternative descriptions of means of electrolyte circulation, heat and water management. Some discussion of stationary systems is provided in Kiros et al. [32] and Lindstrom [61] however no specific information concerning system configuration or operating conditions is provided. Consideration of systems issues must therefore be considered on the basis of the published ZEVCO experience alone.

The Alkaline system requires the control of three fluid loops including the reactant fuel and oxidant and the recirculating electrolyte. The fuel and oxidant loops are operated at marginally higher than ambient pressures and are thus very simple. The fuel loop contains a simple water knockout and re-injection into the input stream via a venturi pump. The air loop contains no recirculation. No details of the connection of the air loop to air scrubbing apparatus are provided in any of the published reports. This connection is, however, quite important for successful system operation.

Although no specific systems descriptions of entrapped electrolyte AFCs are provided, they have been discussed by Kordesch and Simader [48]. Entrapment of the electrolyte by suspension in an asbestos matrix forces the system design to rely on fuel or oxidant flow to pick up product water and heat. This significantly complicates the design of these gas flow loops, forcing similar considerations as are applied in the design of PEM systems. Cell cooling via the air loop would result in the flow of large amounts of scrubbed air through the cell, a practice that would be wasteful of the soda lime scrubbing in conventional alkaline cell operation. Availability of low cost or more effective means of purifying the air stream in an alkaline cell may therefore improve the feasibility of this different mode of operation.

There is no discussion of sealing in any of the published reports. This is not unusual as the problem of sealing is seldom discussed in open literature for any type of fuel cell (but is nonetheless a critical component for successful operation). The dominant design continues to be based on edge-collected cells assembled in “modules” that have a stacked arrangement (cathode–anode–cathode). This is strange, as we would have expected a bipolar stacking arrangement to replace this edge-collected structure by now. A bipolar stacking arrangement is called for by Kordesch and Simader [48] and was developed by Tomantschger et al. [30]. Gas manifolding, electrolyte recirculation and current collection all require different approaches in the bipolar stack arrangement and effective sealing technology is key to the success. Since Tomantschger et al. published their paper; there has been no other reported progress on bipolar AFC technology. We remain curious about the demise of the bipolar alkaline stack.

3.3.1. *Electrolyte circulation*

The liquid electrolyte is circulated, allowing the possibility of removing product water and heat from the cell and also allowing the possibility of removing carbonates from the electrolyte to maintain cell performance. The circulation of the electrolyte within the alkaline cell is analogous to the circulation of cooling within PEM cells with roughly equivalent complexity for both. The major difference between the two is that the alkaline cell must deal with a highly caustic electrolyte, requiring more care than the simple deionized water used in PEM technology.

Given the opportunity to develop alkaline cell electrodes that will not clog with precipitated carbonates, the circulation may provide an opportunity to clean or replace the electrolyte much as engine oil is replaced in conventional internal combustion engines. None of the reports discusses this as a normal operating strategy, however.

Kordesch and Simader [48] point out that the circulation of the electrolyte can introduce parasitic current loops within the stack but they do not indicate any serious negative effects, which may result from these. Tomantschger et al. [30] include an explicit electrolyte heating loop in his designs, suggesting the use of the electrolyte to bring the cell up to operating temperature for low temperature startup.

3.3.2. Salvage

There are no published reports comparing the lifecycle environmental impact of AFCs with PEM fuel cells or internal combustion engines. We would expect the alkaline cell to fare well in such a comparison due to the material composition of the cell. The alkaline cell can be manufactured without the use of a noble metal catalyst that while contributing directly to lower short-term costs also has environmental benefits [62].

The simplicity of the electrolyte used in the alkaline cells provides a distinct advantage compared to PEM. There are no major supply security issues associated with AFC's, and while familiar proton exchange membrane manufacturers presently make their products widely available it is possible that large market players or government regulations could limit the distribution of these materials in future. Further, the disposal of current PEM membranes presents an environmental hazard due to the reliance on fluoropolymers, which are not recyclable [63]. These considerations are important for the environmentally sensitive European market or for global markets in developing countries where material supply security is a major concern.

3.4. Lifetime and duty cycle information

A number of long-term tests have been performed with AFC systems and cells. Most of these long-term tests were performed in an attempt to gain an understanding of carbon dioxide poisoning with few test reporting the result of operation to ultimate failure. Nonetheless it is possible to obtain a good sense of AFC life from the published reports. As with other technical aspects of AFC systems, the literature divides naturally into two groups consisting of reported performance for the Kordesch/Elenco/ZEVCO technology, which tends to provide the most complete *system* performance information, and reports from other research groups which tends to be more oriented toward single cell and component testing. Results reported from these two groups will be discussed separately.

3.4.1. Zevco long term tests

The earliest mention found for a long-term test with a Zevco (or Elenco, as it was then called) stack stated that the degradation of the stacks over the course of 5000 operating hours was 12–14 mV/1000 h [16]. De Geeter et al. [4] re-iterate this 5000 h figure as the minimum operational life of a standard Zevco module. Operational parameters are missing from these reports, except the statement that some of the modules tested were operated at full power.

Vegas et al. [14] tested an Elenco module over the course of 1000 operational hours with a varied and largely unstructured operating duty cycle over the duration of the test. Highlights of this test include over 100 startup and shutdown procedures, repeated continuous operation for more than 100 h at a time and at least one six month period where the system was not operated at all. The results they obtained show that performance of the module degraded significantly throughout the duration of the test. Even so, the system remained operational and reasonably functional after 1000 h of operation.

The information presented above is supported by Michael [2] who states that a 50–70 $\mathrm{mW/cm^2}$ power reduction (nearly 30%) is found for the 6000 h test of a 500 W stack. This paper stated that the test was non-continuous but did not give any information on electrolyte replenishment or replacement. The tests were performed at the standard operating conditions for the Zevco modules of 100 $\mathrm{mA/cm^2}$.

Zevco's standard for determining if their cells are operating appropriately consists of measuring the degradation after 3000 h of operation. The cells are considered to be working effectively if the drop over these 3000 h of operation is less than 10% [2].

3.4.2. Other long term tests

A number of other long term tests on half cells and space system fuel cells have been reported as well as some data on the performance of other fuel cell systems.

Tomantschger et al. [30] performed electrode tests under continuous operation for over 3500 h. These tests, which were performed at 100 $\mathrm{mA/cm^2}$, 65°C with 12 N KOH, showed a significant decrease in the hydrogen electrode voltage of 50–100 mV over the course of 3000 h. The oxidant electrode, which was operated on air, showed a slightly lowered potential from 1500–3000 h but this drop was reversed after 3000 h. No further discussion is given regarding this effect.

Tomantschger et al. [64] also reported on 1000 h tests at 100 $\mathrm{mA/cm^2}$ with varied temperature. From these results, they determined that the internal resistance of the cell increased with time and a change to silver electrodes from the nickel that was originally used gave significantly improved

Table 4
Summary of reported Alkaline Fuel Cell lifetimes

Date	Hours	Current density (mA/cm^2)	System information	Source
1986	3500	100	Electrodes	[30]
1987	5000	100	Elenco module	[16]
1990	> 2000	Unknown	Siemens BZA4	[58]
1991	424& 600	100	Electrode tests	[65]
1994	3500	100	Electrode tests	[66]
1994	200	160 mV Overpotential	Electrode tests	[37,38]
1996	15,000	Unknown	Not stated	[48]
1996	15,000	Unknown	Orbiter fuel cell	[59]
1998	1000	Varied	Elenco module	[14]
1999	> 5000	100	Zevco module	[4]
1999	4000	Unknown	From JPL	[13]
1999	11,000	100	Anode electrode	[32]
2000	6000	100	Zevco module	[2]
2000	6000	100	Zevco module	[2]

performance. The magnitude of the improvement was not quantified.

Strasser [58] tested four Siemens BZA4 modules and found that each module showed a similar performance drop over the course of the test. A drop of approximately 50 mV was observed over the course of this 700 h test performed at 80°C with pure hydrogen and oxygen at 2.3 and 2.1 bars, respectively. Tests of several thousand hours are briefly mentioned but no details are provided.

Lamminen et al. [65] developed electrodes that were constructed with different catalysts. At 100 mA/cm^2 they ran one sample intermittently for 424 h while another sample was tested for over 600 h. They found that the performance degradation was as great or greater when no power was drawn from the cell.

Kordesch, who learned from his early Austin A40 experiment that draining the electrolyte from the cells when the system was not operational greatly enhanced the lifetime, has made this observation repeatedly.

Gulzow et al. [66] found that they could run a cell for 1000 h at 100 mA/cm^2 with a 17 μV/h degradation of cell voltage with or without CO_2 in the air stream. Al-Saleh et al. [37,38] performed an excellent 200 h test of an AFC system in relation to carbon dioxide performance, which was discussed in Section 3.2.1.

Kordesch and Simader [48] and Khalidi et al. [59] both refer to a 15,000 h lifetime for AFCs. Kordesch gives no information regarding the source of this figure while Khalidi et al. mention that this is for small installations of the Orbiter fuel cell with no other information. Kordesch et al. [13] quote a figure of 4000 h from JPL with no other data given.

Kiros et al. [32] showed the performance of an anode electrode over the course of 11,0000 h. At 100 mA/cm^2 they found a decay rate of 3–4 μV/h. They do mention changing their electrolyte at regular intervals to avoid carbonate buildup, which could change the performance characteristics of the test.

3.4.3. Summary of AFC lifetimes

The lifetime of an AFC can, in general, be well over 5000 h for inexpensive terrestrial AFCs and has been shown to be significantly over 10, 000 h for space application AFCs. It would not be unreasonable to assume, given a significant development effort that the lifetime of AFC cells could be well over 15, 000 h. Table 4 summarizes the different operational lifetime figures discussed above.

The only discussion of operating duty cycles and procedures for alkaline cells is provided by Kordesch [9] in the context of the Austin A40 fuel cell powered car. The electrolyte was drained nightly and a nitrogen purge was used to neutralize the cells during the shutdown and into inactive operation. Despite these operational issues, Kordesch claims that the system could be returned to operational condition within a few minutes.

4. Cost analysis

AFC technology, evaluated from a purely technical perspective, has the potential to compete with other low temperature fuel cell technologies. Although the alkaline technology has been largely neglected in the last ten years, mostly due to the apparent CO_2 poisoning issue, the foregoing section has shown that there are no obvious technical reasons to discount its potential for useful applications. This general conclusion raises the questions of relative costs between AFC technology and its competitors in order to better understand the potential economic competitiveness of the AFC technology.

In this section we present a review of the cost information available for AFC technology and where possible compare

Table 5
Summary of low power ambient air fuel cell prices [71–73]

Company (Fuel Cell Product)	Nominal Power	Type of Fuel Cell	Price (US$)
Astris (LC200-16)	240 W	AFC	2400
H-Power (PowerPEM-PS250)	250 W	PEMFC	5700
DAIS-Analytic (DAC-200)	200 W	PEMFC	8500

these cost estimates to equivalent PEM costs. The reader is cautioned that while the cost comparisons included in this section are based on the best available information at the time of writing, we have been faced with extrapolating costs in some cases, estimating costs in others and comparing cost information provided for different purposes. For example, most of the AFC cost information presented is based on ZEVCO provided data from recent conference publications. Such data, though likely optimistic, is nonetheless rooted in a hard estimate of short-term costs and must be believable by investors with a three to five year time horizon for return on investment. Similar cost estimates for PEM systems are not available due to their proprietary nature. The PEM cost estimates we show are derived from sources, which apply standard industrial forecasting methods assuming full-scale automotive production, is achieved [67] as a means of forecasting long-term trends in technology development. As a result we tend to be more confidant in the accuracy of the alkaline cost data than in the potentially over-optimistic PEM cost projections.

Beyond costs of components and stacks, overall fuel cell power plant costs must be considered. The overall cost of a 50 kW PEM fuel cell power plant is estimated at US $2103 [67]. This is the ultimate cost against which any engine replacement system will have to compete. The ZEVCO strategy is to develop a hybrid fuel cell/battery system for vehicle applications. This goal may be achieved using an AFC, an ambient air PEM fuel cell or a compressed air PEM fuel cell. In the following analysis we will derive production volume cost estimates for these three options and compare them to the overall fuel cell engine costs.

4.1. Gross costs and commercial estimates

There is general agreement in the literature that AFC costs are lower or at least equivalent to other fuel cell technologies, both in terms of material and production costs. Citing calculations of the costs of fuel cell systems by DLR (Germany), ZSW (Germany), Hoechst (Germany) and the Royal Institute of Technology (Sweden), Gulzow [21] states: “All calculations show that the stack costs are similar to all other low temperature systems [and] the production cost for the AFC systems seem to be the lowest”. Their estimates give a conservative price of **US$ 400–500/kW** using 1996 technologies and knowledge in large-scale production. They also mention a 5–10 times higher production cost for small-scale production.

Other projected general estimates for AFC material or stack costs range from US$ 80/kW to US$ 265/kW (figures adjusted to 2000 US$) [18,30,13].

Although lacking any hard numerical figures, a recent report from ETSU (UK) makes some interesting remarks regarding the cost of AFCs [2]. One underlines the fact that “current AFC stack designs have a modest performance compared with [PEMFC], but the AFC stack is relatively cheap even at low manufacturing volumes”. The author then emphasizes a key difference at this point between PEMFC and AFC system: “Whilst high manufacturing volumes will be essential for [PEMFCs] to beat the target costs for cars, the AFC could become competitive as a battery charger for electric vehicles”. Regarding the battery-charger approach taken by Zevco to commercialize its AFC systems, he states: “There seems to be no evidence to suggest that the AFC could not be manufactured in small volumes at prices necessary to be competitive as a battery range extender...”.

The cost of commercially available low-power AFCs and PEMFCs is shown in Table 5. Although not representative of higher power fuel cell costs and based on a very small sample, these figures seem to support the cost advantage of AFCs over PEMFCs (2–4 times cheaper in this case).

4.2. Materials and manufacturing

Stack cost has a large influence upon the system cost of any fuel cell system. As such, a detailed breakdown of the stack materials and manufacturing costs is needed to determine the competitive position of alkaline and PEM fuel cell technologies. This section first presents an overview of the different material components of both AFC and PEM stacks and then compiles the available cost estimates to provide the basis for the remainder of the analysis.

4.2.1. AFC stack materials

Table 6 lists the materials currently used in the various AFC cells and systems discussed in the literature.

Potential improvements in the AFC stack materials include the reduction of the catalyst loadings, as well as development of cobalt oxide based catalysts and replacement of the nickel mesh current collectors with a cheaper metal mesh [3].

Table 6
Materials and manufacturing processes for AFC stacks [4,5,21]

Component	Materials	Manufacturing Processes
Electrodes		
Anode	PTFE powder graphite powder catalyst: (Pt or Pd 0.12–0.5 mg/cm^2) Ni–Al, Ag	Mechanical process involving grinding, dispersion, filtering, rolling and drying
Cathode	PTFE powder graphite powder catalyst: Pt	Mechanical process involving grinding, dispersion, filtering, rolling and drying
White layer (for both anode and cathode)	PTFE powder	Pre-forming and rolling
Module		
Current collectors	Nickel mesh	Pressed to black and white layers (as above)
Plastic frames	ABS plastic	Injection molding and manual assembly with electrodes
Spacers	Unknown	
Stack assembly		Plastic frames are friction-welded to module casing for sealing

Table 7
Materials and manufacturing processes for PEMFC stacks [6,51]

Component	Materials	Manufacturing Processes
MEA		
Membrane	Polymer matrix with attached sulfonic acid groups E.g. Nafion, BAM 3G, etc.	Complex chemical process
Electrode substrate	Carbon paper, PTFE	Attached to membrane through hot pressing
Catalyst	Pt (0.4–4 mg/cm^2)	Deposited between the electrode substrate and the membrane
Other Stack Components		
Flow field plates (including cooling plates)	Graphite, stainless steel, carbon polymers, etc.	Machined out of bulk material, stamped, injection molded
Non-repeating components	Off the shelf components	Simple machining

4.2.2. PEMFC stack materials

Table 7 gives a summary of the PEMFC stack materials and manufacturing processes.

A number of potential improvements are foreseen for both manufacturing and materials in PEMFC stacks. These include the reduction of the catalyst loading down to 0.04 mg/cm^2 through improved deposition techniques, different nanostructure catalyst supports, the use of carbon composite materials and stamped metal sheets for the flow field plates and the reduction of the MEA thickness [68].

4.2.3. AFC system costs

Table 8 lists the projected costs of a Zevco stack module. This table is based on the data provided by Zevco in recent conferences and public presentations but has not been published in a citable reference.

No information on the assembly or manufacturing costs has been specifically stated for AFCs. However, it is reasonable to assume that the manufacturing costs are included in the component costs. The cost of final assembly, especially for larger volume manufacturing, is assumed to be minimal.

Table 8
Costs of AFC stack components [8]*

Component	Current (US$/kW)	Projected (US$/kW)
Total stack costs	1750	205

*Note: Converted from ECU/kW to US$/kW on a 1:0.925 basis.

4.2.4. PEMFC stack costs

PEMFC stack costs have been reported in a number of papers and reports, with current stack cost estimates ranging from \$500/kW [69] to \$5000/kW [70]. Optimistic cost projections for a 70 kW stack, for a typical automotive production volume of 50,000 units per year, produce a lower bound cost estimate of \$20/kW [67].

Table 9 summarizes the two extreme cost estimates available in the literature. The data of Ekdunge and Raberg [70] is summarized in the second column and covers material costs only for small-scale laboratory production of a 75 kW unit using "conventional" materials. The data of James et al. [67], summarized in column 3, is on the other hand an estimate that includes material, manufacturing and assembly costs for large-scale production of 30–90 kW stacks using "advanced materials".

Ekdunge assumed a catalyst loading of 16 g/kW, which corresponds to around 8 mg/cm^2. With today's catalyst loadings, this could be decreased by nearly an order of magnitude, reducing the cost estimate by around \$200. Also, the cost of the flow field plates as stated by Ekdunge and Raberg [70] may currently be significantly lower with the use of different materials.

4.3. Impact of production volume

Fuel cell technology presently has no established market and will thus inevitably go through several phases of niche market penetration before widespread deployment of the technology occurs. This means that while ultimate high volume production costs may favor a particular technological option there may be short-term cost advantages for other technologies. In particular, we are interested to determine if AFCs possess any inherent cost advantage in small volume production that is more indicative of early fuel cell markets.

No study presenting cost estimates of AFC stacks at very high volumes has been found. To estimate low volume production costs we have used the lowest power density ZEVCO Mark II costs described in the previous section. Conversely, our high volume cost estimate is derived on the highest performance projections provided by ZEVCO.

There are many sources providing high volume mass production cost estimates of PEMFC systems. All these results are within the **US$ 20–50/kW range**. Directed Technologies completed one particularly thorough report for the Ford Motor Company [67]. Most cost estimates for PEMFC system components at high volumes, used in the present analysis, are taken from this report. The Directed Technologies report provided cost estimates for PEM fuel cell systems in the 30–90 kW range. These cost estimates have been extrapolated to estimate the costs in the 7 kW range, details of this extrapolation are included in Appendix A.

The estimated stack costs for both alkaline and PEM fuel cell technology are compared to each other at different production volumes in Table 10. The high volume cost estimate for AFC was deduced by extrapolating the data of DeGeeter [4] and Michael [2]. At low volumes anticipated in early markets the PEM technology is between 3 and 9 times more costly than the alkaline technology. However, this trend reverses at very high volume production rates. The lower costs are attributable to lower material costs and simple manufacturing technologies. The PEM cost reductions are achieved through the anticipated gains that will be made by exploiting economies of scale in manufacturing materials and stack components.

4.4. Extrapolation to ambient air PEM

The possibility of an ambient air PEM fuel cell being used as a "battery range extender" constitutes a major threat to

Table 9
Costs of PEMFC components [67,70]

Component	1998 PEMFC materials (US$/kW)	500,000 unit per year production (US$/kW)	% (500,000 units per year)
Membrane	120	0.40	2%
Catalyst	243	8.20	41%
Gas diffusion electrode	31	3.00	15%
Flow field plates (including cooling plates)	825	6.00	30%
Non-repeating components	1	1.00	5%
Assembly		1.40	7%
Total	1220	20	100%

Table 10
Effect of production volumes on fuel cell costs

	AFC stack (US$/kW)	PEMFC stack (US$/kW)	$ PEMFC / $ AFC
Small batch fabrication	1750	2000–5000 [70,74]	1.2–2.9
Small-scale manufacturing (100s, 1000s?) Improved AFC performance	205	500–1500* [69,75]	2.5–7
High volume production (Unknown volume for AFC) (500,000 units/yr for PEMFC)	155	20 [67] (50-kW unit) 60 extrapolated from [67] (7-kW unit)	0.13–0.4

*$1500/kW includes ancillaries.

Table 11
Ambient air PEMFC cost estimate table

	High cost estimate	Low cost estimate
Compressed PEMFC cost (US$/kW)	1220	60
Multiplication factor for running at ambient	5	3
Ambient PEMFC cost (US$/kW)	6100	180

low power density applications of alkaline fuel cell system technology. Therefore, we are interested in estimating the cost of such a system. To produce this estimate, the Directed Technologies calculations for PEMFC stack costs [67] have been extrapolated to an ambient air PEMFC.

Current ambient air PEMFC systems, as mentioned in Section 2.1.5, operate at roughly 200 mA/cm^2 compared to compressed air PEMFCs that produce over 1 A/cm^2. Therefore, for the same power output an air breathing PEM stack will require at least 5 times the active area of a compressed air stack. While ambient air operation may imply a simpler stack design overall, the amount of membrane material and catalyst required will be several times higher than for the compressed air counterpart.

Upper and lower bound cost estimates for ambient air PEM stacks can be constructed from this information as shown in Table 11. The high cost estimate is formed by multiplying the high compressed stack cost estimate by 5 to estimate a "worst case" scenario. The low cost, best-case estimate is formed by multiplying the low compressed stack costs for a 7 kW stack by 3.

4.5. *Balance of plant*

Balance of plant components that need to be considered for AFCs include the air blower, CO$_2$ scrubber, electrolyte circulation and nitrogen purging. PEM balance of plant requirements differ because of the need for air compression at significantly higher pressures than alkaline, humidification of reactant gases and cooling systems. Cost estimates for PEM balance of plant have been previously published [67].

Although the overall control system required for operation an alkaline hybrid system should be significantly less complex than for a PEM fuel cell engine, this saving may be more than offset by cost of power electronics involved in managing the battery system. Furthermore, if an ambient air PEM system were used to replace the alkaline system in vehicle applications the controller costs would be equivalent.

4.5.1. *AFC peripherals*

Most of the components used in the balance of plant of the AFC system are relatively standard equipment, with the notable exception of the CO$_2$-scrubber. Their aggregate cost does not seem to be a major obstacle to AFC system commercialization.

4.5.1.1. Air blower. For a 5-kW system, Zevco uses a 350-W pump in the air circuit, but no optimization appears to have gone into the selection of this component. De Geeter [4] suggests that reduction of blower power by a factor of five is anticipated through easily achievable redesign of the airflow path.

4.5.1.2. CO$_2$-*surubber.* No cost data has been found for the soda lime scrubber proposed, but some numbers are available for the required quantity and cost of soda lime. We anticipate that the cost of the soda lime will become the significant component of CO$_2$ scrubbing because the reactor vessel containing the soda lime is composed of a passive container operating without any high pressures or temperatures. The cost of soda lime used over the lifetime of the cell is provided in Section 4.6.1.

Table 12
AFC peripheral costs

	Cost (US$)	%
Air blower	14	5.5%
CO_2 scrubber	14	5.5%
H_2 recirculation ejector	22	8.6%
Electrolyte recirculation	100	39.2%
Nitrogen purge	15	5.9%
Electronic engine control (EEC)	50	19.6%
Piping, valving, misc.	40	15.7%
Total periph. sys. cost (incl. mark-up and cost contingency)	255	100%

4.5.1.3. *Electrolyte recirculation loop.*

The main components of the alkaline electrolyte loop are the heater, a 50-W electrolyte pump, a small heat exchanger and a ventilator. The cost of this subsystem are assumed to be roughly equivalent to the cost of the coolant loop in conventional PEM technology, which we estimate to be US$ 100 in mass production [67]. Unlike PEM fuel cells, the electrolyte in AFCs requires maintenance and incurs an operational cost over the lifetime of the cell. This is discussed in Section 3.3.1.

4.5.1.4. *Water management.*

Water management is relatively straightforward in the Zevco AFC system and incurs a minimal cost. The associated components are mainly a small water tank and a water condenser.

4.5.1.5. *Nitrogen purge.*

The use of a Nitrogen purge to remove reactant gases from AFCs is shown on most system diagrams from the ZEVCO system [4,15]. However, no details of the nitrogen purge system are available, and some designs claim not to require this component.

4.5.2. *Alkaline peripheral costs*

Based on the foregoing we are able to construct an estimate of the cost for balance of plant components required in AFC systems, as shown in Table 12. Most estimates are adapted from those of a PEMFC component with equivalent function.

4.5.3. *Compressed PEMFC peripherals*

In a PEM fuel cell system the oxidant compression system, electronic engine controls, radiator system and humidifier system contribute 89% of the cost of peripheral components. An extrapolation to a 7 kW system of the peripheral costs given in the study by Directed Technologies/Ford (for systems in the range 30–90 kW) [67] is presented in Table 13.

Table 13
PEMFC peripheral costs

	Cost (US$)	%
Air compression subsystem (Compr./Expander/Motor Unit—CMEU)	330	41.4%
Air humidifier subsystem	65	8.1%
H_2 recirculation ejector	22	2.8%
Radiator subsystem	92	11.5%
DI filter	14	1.8%
Electronic engine control (EEC)	220	27.5%
Piping, valving, misc.	55	6.9%
Total periph. sys. cost (incl. mark-up and cost contingency)	798	100%

4.5.4. *Ambient air PEM peripherals*

For an ambient air PEMFC system, the peripheral costs are somewhat different than the compressed PEMFC system. The air compressor is replaced with a simpler blower unit and the Electronic Engine Control is vastly reduced in complexity due to the simpler operation of the fuel cell as a battery charger. (Table 14)

Table 14
Estimated peripheral component costs for ambient air PEM systems

	Cost (US$)	%
Air blower	14	5.5%
Air humidifier subsystem	65	25.8%
H_2 recirculation ejector	22	8.6%
Radiator subsystem	50	19.5%
DI filter	14	5.5%
Electronic engine control (EEC)	50	19.5%
Piping, valving, misc.	40	15.6%
Total periph. sys. cost (incl. mark-up and cost contingency)	255	100%

4.6. *Cost of consumables*

AFCs consume electrolyte and soda lime. In this section we estimate these costs.

4.6.1. *Soda lime*

Soda lime is consumed in significant quantities in AFCs. In fact it appears that the mass of soda lime used is approximately equal to the mass of hydrogen used in normal cell operation. Therefore, regardless of the simple costs associated with maintaining the soda lime scrubbing unit there is a potentially large intangible cost associated with the regular maintenance required.

Presently, scrubbing technology is able to make use of only 7% of the limestone contained in the scrubber unit, but utilization up to 80% is achievable [2]. Using the rate of 8 kW h/kg for the present technology, we produce the cost

Table 15
Soda lime cost estimate based on bulk cost of $ 0.2/kg, 5000 h cell lifetime at 7 kW

% Utilization	Consumption rate	Lifetime mass	Cost
7%	8 kW h/kg	4500 kg	$900
80%	92 kW h/kg	394 kg	$80

Table 16
Cost of KOH electrolyte

Electrolyte life (h)	Lifetime # changes	Lifetime cost $US
300	17	153
500	10	90
1000	5	45
5000	1	9

estimates for CO_2 scrubbing over the 5000 h, lifetime of the system as shown in Table 15.

4.6.2. *KOH*

A 7 kW AFC system requires 13 kg of 6–9 N KOH solution for the electrolyte, representing a mass of roughly 3 kg of KOH. Although KOH is considered to be a cheap bulk material its cost must be factored into the overall system cost for an AFC.

In small lab scale quantities KOH is available at US$9.00/kg, leading to an estimated cost of US $3.00/kg in bulk. Based on this information and the frequency of electrolyte replenishment over the lifetime of the cell the total electrolyte costs are estimated as shown in Table 16.

4.7. *System cost estimates*

By combining the information presented in the previous sections upper and lower bounds for the cost of three competing 7 kW fuel cell systems are produced, as shown in Table 17. Apart from being deduced from commercial data, the alkaline estimates have a total cost range that is a factor of 6, compared to a range of 28 for the ambient air PEM estimate, reflecting our uncertainty here. Gulzow [21] quotes a figure of $400–$500/kW for an AFC system using the technology of the time for high volume production. This number falls in between the two figures obtained for an AFC system.

This analysis indicates AFC systems are cost competitive with comparably sized PEMFC systems, at least for low power. This advantage remains for all production volumes, but is most significant at low and medium production volumes.

However, it should be noted that the 7 kW alkaline system would be competing with a 50 kW PEMFC system. Directed Technologies has estimated that the total system cost for a 50 kW PEMFC system would be about $2100 for production volumes of 500,000 [67]. This means that extra components required to complete the alkaline hybrid power system (namely batteries) must cost no more than about $670.

Of interest with this report is the opportunity available for CO_2 scrubbing with novel technologies. The total cost of CO_2 scrubbing in the above system is $94 ($14 for the Canister and $80 for the Soda Lime). Therefore, if we consider the cost of the system without batteries or CO_2 scrubbing we have a cost of $1334. This implies that, to be competitive with a 50 kW PEMFC system, the cost of batteries and CO_2 scrubbing must be less than about $750.

5. Conclusions

In this report we have presented a review of AFC technology to assess its potential from both technical and economic perspectives. Research and development in AFC technology has become largely stagnant during the past decade although we can find no obvious technical or economic reasons for the relative neglect it has received.

AFCs can theoretically outperform PEMFCs and some of the earliest pressurized AFC systems showed current densities much higher than those achieved today with current PEM technology. Concerns about the low power density achieved by current AFC technology are misplaced, as the current AFC designs are directed at low power applications. Ambient air operated AFCs produce current densities comparable to ambient air operated PEMFCs.

Only a single design paradigm has been explored in commercial AFC systems. There is considerable scope for improvement of AFC technology through further research, in particular for the development of new architectures for AFC operation. There is no strong IP position to prohibit the further development of AFCs, nor are there any material supply issues to potentially impede AFC development. AFC technology has the potential to yield major improvements for modest R& D investments.

Contamination of AFCs due to the presence of CO_2 is an issue for sustained system operation. CO_2 in the Cathode air stream definitely poisons the electrolyte and in turn can cause some designs of electrodes to become clogged with carbonate. The use of high current draw from a cell to “electrolyze” the carbonates should be investigated further. The only practical solution to the CO_2 problem currently employed is the use of Soda Lime for scrubbing CO_2 from the air-stream. This is cumbersome, comparatively costly (est. $US 94 per system) and has not been optimized as yet. Development of new means of CO_2 removal from the oxidant stream for an AFC system would address many operational issues associated with AFC stacks. Contamination due to impure hydrogen is another problem that may prohibit the use of AFCs with reformed hydrogen streams, though this contamination seems to be totally reversible.

Current AFC systems have been demonstrated to easily meet the 5000 h lifetime required for traction applications.

Table 17
Total system costs comparison

Component	Compressed PEMFC		Ambient air PEMFC		Ambient air alkaline	
	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound
Stack cost ($/kW)	1220	60	6100	180	643	155
Stack cost	8540	420	42,700	1260	10,942	1084
Balance of plant	798	798	256	256	255	255
Consumables	N/A	N/A	N/A	N/A	1053	89
Total	9338	1218	42,956	1516	12,250	1,428
Total per kW	1334	174	6136	217	1750	204

Table 18
Cost summary for 7 kW PEMFC stack

	Total cost (US$)	Cost per kW (US$/kW)
Stack	$419	$60
System peripherals	$798	$114
Total system cost	$1217	$174

However, electrolyte management issues in AFC's imply a degree of ongoing maintenance not necessary with PEMFC technology. Periodic maintenance is also required for the existing soda lime CO_2 scrubbing. Minimizing maintenance in AFCs is an important topic for development.

Our analysis of costs shows that AFC systems for low power applications including hybrid vehicles are at least competitive with the cost of any equivalent system constructed using PEMFC technology. The AFC system has a low cost stack and low cost peripheral components. An ambient air operated PEM system, while having low cost peripheral components has prohibitively high stack costs. A high pressure PEM system, while enjoying low stack costs, requires expensive peripheral components. Further improvements in AFC technology will only strengthen this competitive position.

Appendix A: 7 kW PEMFC stack cost development

James et al. [67] develop stack and system costs for 30–90 kW PEMFC systems. The data given by James allows for the extrapolation of these costs down to 7 kW. Figure 2 illustrates this extrapolation.

It can be seen that the cost of the stack is much more sensitive to scale than the cost of peripherals. The cost figures developed using this linear extrapolation for a 7 kW stack are given in Table 18.

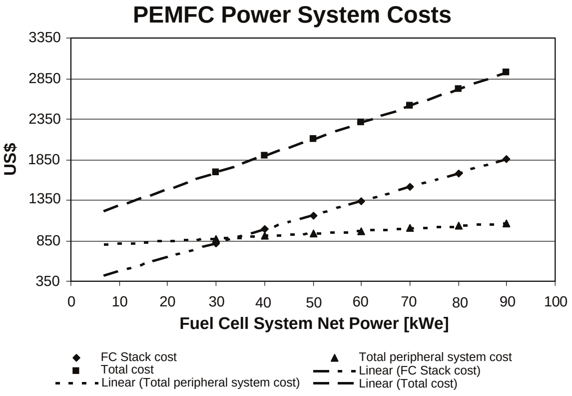

Fig. 2. PEMFC power system costs.

References

[1] Kordesch K. Power Sources for Electric Vehicles. Modern Aspects of Electrochemistry, 10, Plenum Press, New York, 1975. p. 339–443.

[2] Michael PD. An assessment of the prospects for fuel cell-powered cars. ETSU, United Kingdom, 2000.

[3] Zevco Website, (www.zevco.co.uk), last accessed April 5, 2000.

[4] De Geeter E, Mangan M, Spaegen S, Stinissen W, Vennekens G. Alkaline fuel cells for road traction. J Power Sources 1999;80:207–12.

[5] Kivisaari J, Lamminen J, Lampinen MJ, Viitanen M. Preparation and measurement of air electrodes for alkaline fuel cells. J Power Sources 1990;32:233–41.

[6] Blomen LJMJ, Mugerwa MN. Fuel cell systems. New York: Plenum Press, 1993.

[7] Srinivasan S, Enayetullah MA, Somasundaram S, Swan DH, Manko D, Koch H, John Appleby A. Recent advancements in solid polymer electrolyte fuel cell technology with low platinum loading electrodes. Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, IEEE, 1989. p. 1623–9.

[8] Bahar B, Cavalca C, Cleghorn S, Kolde J. Effective selection and use of advanced membrane electrode assemblies. 1998 Fuel Cell Seminar, Palm Springs, 1998. p. 531–4.

[9] Kordesch KV. Outlook for Alkaline Fuel Cell Batteries. From Electrocatalysis to Fuel Cells, Seattle, WA, 1972. p. 157–64.

[10] Kordesch K. Electrochemical Power Generation. International Symposium on Electrochemistry in Industry: New Directions, Plenum Press, New York, 1982.

[11] Kordesch K. Fuel cell R& D—toward a hydrogen economy. Electric Vehicle Develop 1989;8:25–6.

[12] Kordesch K, Gsellmann J, Cifrain M. Revival of alkaline fuel cell hybrid systems for electric vehicles. Proceedings of Fuel Cell Seminar, Palm Springs, 1998.

[13] Kordesch K. Intermittent use of low-cost alkaline fuel cell-hybrid system for electric vehicles. J Power Sources 1999;80:190–7.

[14] Vegas A, Garcia C, Gonzalez A. Experience with an alkaline fuel cell stack: test plant, measurements and analysis of the results. Hydrogen Energy Progress XII, Buenos Aires, 1998. p. 1621–8.

[15] Mangan M, De Geeter E. In: Howard PF, editor. Gaseous hydrogen/alkaline fuel cell car. Ninth Canadian Hydrogen Conference. Vancouver, BC: Canadian Hydrogen Association, 1999.

[16] Van den Broeck H, et al. Status of Elenco's alkaline fuel cell technology. Intersociety Energy Conversion Engineering Conference Proceedings, Philadelphia, 1987.

[17] Van den Broek H, et al. Hybrid fuel cell battery city bus eureka project. 1994 Fuel Cell Seminar, San Diego, CA, 1994.

[18] Lindstrom O. A critical assessment of fuel cell technology. Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden, 1993.

[19] Lindstrom O. A critical assessment of fuel cell technology. 1994 Fuel Cell Seminar, San Diego, CA, 1994.

[20] Lindstrom O, et al. Small scale AFC stack technology. 1994 Fuel Cell Seminar, San Diego, CA, 1994.

[21] Gulzow E. Alkaline fuel cells: a critical view. J Power Sources 1996;61:99–104.

[22] International Fuel Cells Website, (www.internationalfuelcells.com), last accessed April 25, 2000.

[23] HyWeb-Gazette, (www.hydrogen.org/news/gazette.html), last accessed April 27, 2000.

[24] Nor J. Personal Communication, Astris Energi, Ontario, Canada, April 6, 2000.

[25] Electric Auto Website, (www.electricauto.com), last accessed April 25, 2000.

[26] Matryonin VI, Ovchinkov AT, Tzedilkin AP. Investigation of the operating parameters influence on H_2–O_2 alkaline fuel cell performance. Int J Hydrogen Energy 1997;22:1047–52.

[27] Martin RE, Manzo MA. In: Goswami DY, editor. Alkaline fuel cell performance investigation. Proceedings of the 23rd Intersociety Energy Conversion Engineering Conference, vol. 2, Denver Colorado, 1988. p. 301–4.

[28] Jo J-H, Yi S-C. A computational simulation of an alkaline fuel cell. J Power Sources 1999;84:87–106.

[29] Binder H, Kohling A, Kuhn WH, Lindner W, Sandstede G. Hydrogen and Methanol Fuel Cells with Air Electrodes in Alkaline Electrolyte. From Electrocatalysis to Fuel Cells, Seattle, WA, 1972. p. 157–64.

[30] Tomantschger K, McClusky F, Oporto L, Reid A, Kordesch K. Development of low cost alkaline fuel cells. J Power Sources 1986;18:317–35.

[31] Swette L, Kopek JA, Copley CC, LaConti AB. Development of single unit acid and alkaline regenerative solid ionomer fuel cells. Intersociety Energy Conversion Engineering Conference Proceedings, Atlanta, GA 1993;1227–32.

[32] Kiros Y, Myren C, Schwartz S, Sampathrajan A, Ramanathan M. Electrode R& D, stack design and performance of biomass-based alkaline fuel cell module. Int J Hydrogen Energy 1999;24:549–64.

[33] Nakagawa T, Tsutsumi A, Yoshida K. Performance of an alkaline fuel cell system using three-dimensional electrodes. Buenos Aires: Hydrogen Energy Progress XII, 1998. p. 1333–8.

[34] Matsuno Y, Suzawa K, Tsutsumi A, Yoshida K. Characteristics of three-phase fluidized-bed electrodes for an alkaline fuel cell cathode. Int J Hydrogen Energy 1996;21:195–9.

[35] Matsuno Y, Tsutsumi A, Yoshida K. Improvement in electrode performance of three-phase fluidized bed electrodes for an alkaline fuel cell cathode. Int J Hydrogen Energy 1997;22:615–20.

[36] Holeschovsky UB, Tester JW, Den WM. Flooded flow fuel cells: a different approach to fuel cell design. J Power Sources 1996;63:63–9.

[37] Al-Saleh MA, Gultekin S, Al-Zakri AS, Celiker H. Effect of carbon dioxide on the performance of Ni/PTFE and Ag/PTFE electrodes in an alkaline fuel cell. J Appl Electrochem 1994;24:575–80.

[38] Al-Saleh MA, Gultekin S, Al-Zakri AS, Celiker H. Performance of porous nickel electrode for alkaline H_2/O_2 fuel cell. Int J Hydrogen Energy 1994;19:713–8.

[39] Al-Saleh MA, Gultekin S, Al-Zakri AS, Khan AAA. Steady state performance of copper impregnated Ni/PTFE gas diffusion electrode in alkaline fuel cell. Int J Hydrogen Energy 1996;21:657–61.

[40] Tanaka S, Hirose N, Tanaki T. Evaluation of Raney-nickel cathodes prepared with aluminum powder and tin powder. Int J Hydrogen Energy 2000;25:481–5.

[41] Lee H-K, Shim J-P, Shim M-J, Kim S-W, Lee J-S. Oxygen reduction behavior with silver alloy catalyst in alkaline media. Material Chem Phys 1996;45:238–42.

[42] Gultekin S, Al-Zakri AS, Al-Saleh MA, Celiker H. Experimental studies and electrochemical kinetic parameters of Raney-silver gas diffusion electrode in hydrogen–oxygen fuel cell. Arabian J Sci Eng 1995;20:635–47.

[43] FCT gas diffusion electrodes, (www.fuelcell.kosone.com/elec.html), last accessed 2/23/00.

[44] Han E, Eroglu I, Turker L. Performance of an alkaline fuel cell with single or double layer electrodes. Int J Hydrogen Energy 2000;25:157–65.

[45] Ahn S, Tatarchuk BJ. Fibrous metal—carbon composite structures as gas diffusion electrodes for use in alkaline electrolyte. J Appl Electrochem 1997;27:9–17.

[46] Li X, Horita K. Electrochemical characterization of carbon black subjected to RF oxygen plasma. Carbon 2000;38:133–8.

[47] Sleem UR, Al-Saleh MA, Al-Zakri AS, Gultekin S. Preparation of Raney-Ni gas diffusion electrode by filtration method for alkaline fuel cells. J Appl Electrochem 1997;27:215–20.

[48] Kordesch K, Gunter S. Fuel cells and their applications. Berlin, Germany: Wiley-VCH, 1996.

[49] Sugawara Y, et al. High performance PEFC in dry condition at atmospheric pressure. 1998 Fuel Cell Seminar, Palm Springs, 1998.

[50] Koschany P. Small multi purpose fuel cell systems. Portable Fuel Cells Proceedings, Lucerne, Switzerland, 1999.

[51] Appleby AJ, Foulkes FR. Fuel cell handbook. Malabar, Florida: Krieger Publishing Company, 1993.

[52] Kinoshita K. Electrochemical oxygen technology. New York: Wiley, 1992.

[53] Ahuja V, Green RK. CO_2 removal from air for alkaline fuel cells operating with liquid hydrogen—heat exchanger development. Int J Hydrogen Energy 1996;21:415–21.

[54] Ahuja V, Green R. Carbon dioxide removal from air for alkaline fuel cells operating with liquid hydrogen—a synergistic advantage. Int J Hydrogen Energy 1998;23:131–7.

[55] Fyke A. An investigation of alkaline and PEM fuel cells. Institute for Integrated Energy Systems, University of Victoria, Canada, 1995.

[56] Gultekin S, Al-Saleh MA, Al-Zakri AS. Effect of CO impurity in H_2 on the performance of Ni/PTFE diffusion electrodes in alkaline fuel cells. Int J Hydrogen Energy 1994;19:181–5.

[57] Kiros Y. Tolerance of gases by the anode for the alkaline fuel cell. 1994 Fuel Cell Seminar, San Diego, CA, 1994.

[58] Strasser K. The design of alkaline fuel cells. J Power Sources 1990;29:149–66.

[59] Khalidi A, Lafage B, Gave G, Clifton MJ, Cezac P. Electrolyte and water transfer through the porous electrodes of an immobilized-alkali hydrogen–oxygen fuel cell. Int J Hydrogen Energy 1996;21:25–31.

[60] Ergul MT, Turker L, Ergolu I. An investigation on the performance optimization of an alkaline fuel cell. Int J Hydrogen Energy 1997;22:1039–45.

[61] Lindstrom O, Lavers W. Cost engineering of power plants with alkaline fuel cells. Int J Hydrogen Energy 1997;22:815–23.

[62] Gerhart G. A comparative life-cycle analysis of proton exchange membrane fuel cells and internal combustion engines. M.A.Sc. Thesis, University of Victoria, Victoria, BC, 1996.

[63] Ferguson J. The Future is Green for BWT, (dailynews.yahoo.com/h/nm/20000313/tc/austria_water_1.html), last accessed 3/14/00.

[64] Tomantschger K, Findlay R, Hanson M, Kordesch K, Srinivasan S. Degradation modes of alkaline fuel cells and their components. J Power Sources 1992;39:21–41.

[65] Lamminen J, Kivisaari J, Lampinen MJ, Viitanen M, Vuorisalo J. Preparation of air electrodes and long run tests. J Electrochem Soc 1991;138:905–8.

[66] Gulzow E, et al. Carbon dioxide tolerance of gas diffusion electrodes for alkaline fuel cells. 1994 Fuel Cell Seminar, San Diego, CA, 1994.

[67] James BD, Lomax Jr FK, Thomas CI, Colella WG. PEM fuel cell power system cost estimates: sulfur-free gasoline partial oxidation and compressed direct hydrogen. Directed Technologies, Inc. for the Ford Motor Co., 1997.

[68] DOE Contractor's Report, Fuel Cells for Transportation 1998, DOE, Washington, DC, 1998.

[69] Nundin M. World fuel cell council. Keynote Lecture presented at the Fuel Cells 2000 Conference. Lucerne, Switzerland, 10–14 July 2000.

[70] Ekdunge P, Raberg M. The fuel cell vehicle analysis of energy use, emissions and cost. Int J Hydrogen Energy 1998;23:381–5.

[71] Astris Energi Website, (www.astrisfuelcell.com), last accessed April 5, 2000.

[72] Dais Analytical Website, (www.daisanalytic.com), last accessed April 27, 2000.

[73] H-Power Promotional Material, H-Power, New Jersey, 2000.

[74] Barbin F. Technical challenges in PEM fuel cell development. Proceedings of the 12th World Hydrogen Energy Conference, Buenos Aires, Argentina, June 1999. p. 1589–97.

[75] Thomas CE, James BD, Lomax FD. Market penetration scenario's for fuel cell vehicles. Int J Hydrogen Energy 1998;23(10):949–66.