

Review of alkaline fuel cell performance

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November 2007

Abstract

The current technological status of alkaline fuel cells (AFC) was reviewed, focusing on small (0.5-5kWe) stationary units suitable for domestic CHP. Performance figures were found that represent the real-world capabilities of the state of the art technology. Both commercial and research systems were considered, so long as they could be suitable for a consumer product.

Information was sourced from open literature where possible, for example from: journal publications, commercial data sheets and reports from field trials. This information was reviewed and modified where necessary to give a standardised view of the technology and avoid biased comparisons. Six categories were investigated: power density, efficiency, lifetime, degradation, cost, and fuel tolerance. All of the consulted information is listed and referenced, and the average for each is given.

This review is part of a series of four that focus on different fuel cell technologies for domestic CHP, available from [1]. The reviews are ongoing, and it is expected the tables of information and final values given will be updated as more information is reviewed. The aim is to keep updated with new technological advances, and to continue broadening the overview of the technology. Please contact the author at the above email address with any citable information that would help to extend this work.

Methodology

The scope of this review was to consider fuel cells for use within a small domestic CHP system; defined as the complete package required to convert natural gas into AC electricity and heat at the point of use. Fuel cells for large stationary and transport applications were also considered with discretion, as some overlap exists between these applications and domestic CHP. While the fuel cells reviewed represent modern or state of the art technology, any novel features have been demonstrated to some extent. They must also have been produced with real-world usage in mind, and not preclude the possibility of making a commercially viable product – e.g. being prohibitively expensive to manufacture or having undemonstrated durability.

A summary of the typical performance of AFC technology is presented in the next section; represented by the mean \pm 1 standard deviation for each category of information ($\mu \pm 1\sigma$). The subsequent sections focus on each of the categories of data, and give a listing of all the consulted information. These tables follow the same format; listing the value found, the year the information came from, and some notes about the data source and the fuel cell in question. For each data source, a reference is given along with an identifying label, stating which of the following types of source the information came from:

- [field] A field trial of fuel cells, giving their performance in a real world situation
- [expt] An independently conducted experiment, typically published in a peer reviewed journal
- [theory] A theoretical calculation, typically for mass production costs
- [lit] A literature review of other data sources
- [market] Marketing information from the purveyors of the fuel cell
- [note] A 'typical value' that was mentioned.

Overview

All of the consulted information is summarised in Table 1, which gives the mean and standard deviation of each set of values. The range covered by 1 standard deviation is also given for convenience; it should be expected that two thirds of current systems fall within these ranges. For a definition of each parameter, please consult the introductions to the following sections.

	Mean	Std Dev	Range	# of refs
Operating Voltage (V)	0.73	0.09	0.64-0.82	
Operating Current (Acm^{-2})	0.16	0.07	0.09-0.24	9
Power Density (Wcm^{-2})	0.12	0.06	0.06-0.18	
Stack Efficiency (HHV)	46%	3.5%	42.5-49.5%	
Net Electrical Efficiency (HHV)	29.5%	2.5%	27-32%	4
Net Total Efficiency (HHV)	87%	-	87%	
Lifetime (kh)	6	2	4-8	13
(years)	0.7	0.2	0.5-0.9	
Degradation (μVh^{-1})	19	10	9-29	6
(voltage loss per year)	23%	12%	11-35%	
Cost	€225 + €325/kW	€225/kW	€225 + €150-600/kW	6

Table 1: Overview of performance of AFC systems.

AFC Electrochemical Performance

The operating voltage, current density and power density of AFC are given in Table 2, along with the type of catalyst used in the cells. Typically, pressurised systems were excluded, as they demonstrate significantly higher performance, but require significantly more costly auxiliary systems – and thus are generally not considered suitable for domestic CHP.

Operating Point (V/cell x Acm ⁻²)	Power Density (Wcm ⁻²)	Cell Type	Year	Description
0.67 x 0.14	0.094	Eident (Pt)	2003	Performance of a 0.8kW stack using 0.52mg/cm ² total Pt loading. ^{[2][expt]}
0.67 x 0.1	0.067	Eident (Pt)	1999	Performance of a 0.4kW Zevco Mark II module. ^{[3][expt]}
0.73±0.10 x 0.19±0.08	0.135 ± 0.065	Multiple	1998- 2000	Average of 6 operating points from 5 different sources, which are not listed separately here. ^{[4][lit]}
0.77 x 0.12	0.092	?	1960	Tests by Karl Kordesch on a 6kW stack for transport. ^{[5][expt]}

Table 2: Electrochemical performance of AFC systems.

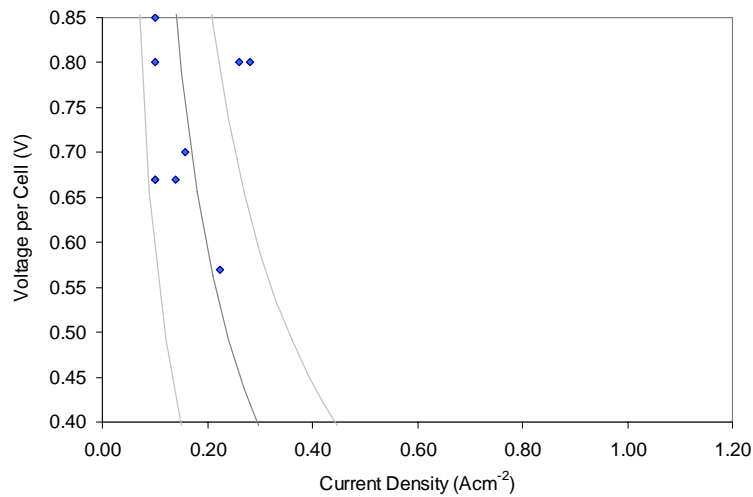


Fig 1: Plot of the operating points of listed AFC systems, with isobars of constant power density at the mean \pm 1 standard deviation.

AFC Efficiency

A number of definitions of efficiency are used relating to fuel cells, giving rise to some confusion and difficulty in comparing systems. A simple, yet strict physical and economic definition was used in this review:

$$\text{Efficiency} = \text{what you get out} / \text{what you put in.}$$

On this basis, the electrical efficiency includes parasitic losses from electrical components (fans, pumps, control circuits), and the power conditioning unit (transformer, inverter). Thermal efficiency is similarly based on the heat delivered to the hot water tank or heating system, net of losses in heat exchangers. The fuel input is natural gas, and so the efficiency of the reforming unit is included.

All efficiencies are quoted relative to the fuel's higher heating value (HHV). In Europe and the USA, the lower heating value (LHV) is typically used, which gives efficiencies 11% higher with natural gas, and 18% higher with hydrogen. The reasons for using HHV were threefold:

- In the UK, domestic customers pay for natural gas based on the HHV energy content
- Domestic CHP units can conveniently condense the flue gasses, making the latent heat of the water content available for extraction
- A rudimentary understanding of thermodynamics suggests that reported efficiencies over 100% (which are typically achieved by condensing boilers) are simply implausible.

The original efficiency quoted from each source is given, with a set of notes to explain what the measurement relates to:

- LHV, HHV: The heating value used
- NG, P-NG, H, P-H: The fuel used: natural gas, pressurised natural-gas, hydrogen, pressurised hydrogen
- AC, DC: Whether inversion of the stack electrical output is included.
- G, N: Whether the value is gross (exclusive) or net (inclusive) of parasitic losses.

For each quoted value, estimates for the stack and system efficiency (η_{stack} and η_{system}) are given, based on the following definitions:

- Stack efficiency is for an ambient pressure hydrogen fuelled system, excluding all ancillary losses, but including the fuel utilisation
- System efficiency is for a natural gas fuelled system, including all reforming and electrical losses

The efficiencies of the mentioned ancillary components were reviewed in a similar manner to the fuel cell technology itself, resulting in the following estimates that have been used:

- Power conditioning: $88 \pm 4\%$ (4 references)
(*inverter and transformer*)
- Other equipment: $94 \pm 2\%$ (4 references)
(*i.e. 6% parasitic losses from pumps, etc.*)
- Steam Reformer: $77.5 \pm 4\%$ (3 references)
(*steam reformation was assumed due to its higher efficiency*)_[6]

The quoted values, with estimates for stack and system efficiency are given in Table 3 to a precision of 0.5%. The variation in efficiency over the range of power output (the part load performance) was also given in some sources, and is plotted relative to the efficiency at full power in Figure 2.

η_{elec} (quoted)	η_{total} (quoted)	η_{system} (HHV)	η_{stack} (HHV)	Cell Type	Year	Description
51% LHV, H, DC		28.5%	44.5%	Eident (Pt)	2003	Table 2, Row 1. Performance of 0.8kW stack.
45% HHV, P-H, DC, N	87%	30.5%	48%	Eident (Pt)	2006	Independent Power's Pulsar-6, 6kW stack operating on 4-6bar H ₂ and ambient air. ^{[7][marketing]}
55% LHV, P-H, DC, N		31.5%	49.5%	Astris (Ni/Ag)? ¹	2004	Astris-E8 2.4kW stack, operating on 6-200bar H ₂ and ambient air. ^{[8][marketing]}
47% LHV, H, DC, N		27%	42.5%	Eident (Pt)	1999	Table 2, Row 2. Performance of Zevco Mark II.

Table 3: Efficiency of AFC systems.

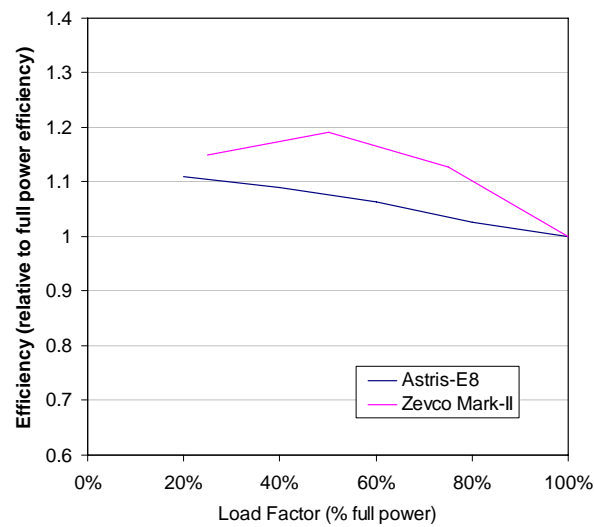


Fig 2: Part load efficiency of AFC systems

¹ It is only assumed that Astris use Ni/Ag, electrodes are only described as “containing no platinum”.

AFC Lifetime

The demonstrated lifetime and rate of voltage degradation of AFC are given in Table 4. The lifetime and failure rates of system peripherals and stacking mechanisms are equally as important as for the individual cells, and so assessments of entire CHP systems were preferred. However, the majority of published information focuses on single cells in laboratory conditions, which are expected to display higher durability due to the more amenable operating conditions.

Note: $1\mu\text{Vh}^{-1} = 1\text{mV per } 1000 \text{ hours} = 1.2\% \text{ loss of voltage per year}$.

Lifetime (kh)	Degradation (μVh^{-1})	Year	Cell Type	Description
	25	UTC (Pt)	c.1970	Running on H_2/O_2 during space missions. ^{[9][note]}
>8		Siemens (Ni/Ag)	1986	Achieved by ~20 units, with 15kh mentioned as the maximum seen. ^{[9, 10][note]}
>5	13	Elenco (Pt)	1987	Degradation tests show minimum lifetime to be 5000h, reiterated by Zevco tests. ^{[3, 4][expt]}
6		Elenco (Pt)	1987	Mentioned Elenco tests into CO_2 poisoning conducted over 6000h. ^{[4][note]}
5-8 min. 15-20 max.		<i>Multiple..</i>	~1992	5-8kh system lifetimes ‘have been established many times’, 15-20kh is the highest known. ^{[2][lit]}
>5 15 est.	17	DLR (Ag)	1996	Found over 3500h in half-cell tests at 0.1 or 0.15A. 15kh lifetime predicted for a full module with circulating, changeable electrolyte. The module was never built. ^{[11, 12][expt]}
11	3.4	KTH (Pt/Pd)	1999	Half cell test at 0.1A, with intermittent polarisation at high current density and electrolyte changes. ^{[13][expt]}
	24	KTH (Ni)	2000	Half cell test at 0.1A over 1500h. Unoptimised electrode hydrophobicity thought to be the cause of rapid decay. ^{[14][expt]}
4.9 ± 1.1		<i>Multiple..</i>	1986- 2000	Average of 6 lifetimes presented from 5 different sources that are not repeated here. ^{[4][lit]}
	5-10 @ 0.1A 20 @ 0.2A	Eident (Pt)	2003	Single V1.1 cells when operating at 0.67V x 0.15A during a 2800h test, with electrolyte replacement. ^{[2][expt]}
	32	Eident (Pt)	2003	A V1.1 modules is expected to lose 10% power over 2500h. ^{[2][note]}
5 min. 8 max.		Astris (Ni/Ag?)	2006	Internal tests ‘consistently see 5kh’ with new carbon materials. ^{[15, 16][market]}

Table 4: Lifetime and degradation of AFC.

AFC Cost

Cost estimates for mass produced AFC systems were sought, to give an approximation of the retail price if the technology were to reach commercialisation and widespread use. These costs are intended to reflect a state of the art system manufactured with present day materials and technologies at high volume.

Current retail prices for fuel cells are in the range of €10,000-100,000+ per kW due to the massive embedded research and development costs, and the high cost of manufacturing on an individual or low volume basis. These additional expenses would be greatly reduced if systems were sold by the thousands, making the retail price tend towards the cost of materials and energy inputs during construction.

The assumptions used in each cost estimate tend to differ widely, as they were concerned with different scenarios – e.g. current or future performance of the fuel cell; residential or industrial CHP units. When sufficient detail was given in the estimate, these assumptions were altered to conform to the other information presented in this report. Typical examples are lowering the power density of the fuel cells and thus increasing the number of cells required to achieve a given power output; or increasing the price of platinum to reflect current prices. The individual modifications are given as footnotes to Table 5.

All costs have been converted to 2007 Euros for consistency, based on a global inflation of 2.5% per annum (0% for Japan), and exchange rates of 160¥ = \$1.30 = £0.70 = €1. The costs are split into the following categories:

- The fuel cell stack, which are typically quoted per kW of electrical capacity
- The balance of plant (BOP), which consists of all ancillary equipment
- Operation and maintenance, which are the costs that occur during the operating lifetime

Stack Cost	BOP Cost	O & M Cost (/MWh)	Cell Type	Year	Description
€500/kW (materials only)			Eident (Pt)	2003	Quoted bill of materials required to produce V1.1 modules. Presumably assuming zero assembly cost, €110-130 of this was Pt ² . ^{[2][note]}
€220/kW (materials only)			Astris (Ni/Ag)?	2006	Claim about the Astris Powerstack M-250. ^{[17][market]}
€400-500/kW			Multiple	1992-1994	Based on a review of reports from DLR, LBST, ZSW, Hoechst & The Royal Institute of Technology (Stockholm). ^{[11][lit]}
€130-560/kW	€225	€2-26 (Consumed soda lime & KOH)	Multiple	2001	Estimate from literature and commercial information. Based on high-volume manufacture of a H ₂ /air system. ^{[4][lit/theory]}
€75-240/kW			Multiple	1986, 1993, 1999	A range of projected general estimates for stack or material costs. Taken from three sources not mentioned here. ^{[4][note]}
€200/kW			Zevco (Pt)	1998	Projected cost of a Zevco module, sale cost at the time was €1600/kW. ^{[4][market/note]}

Table 5: Cost estimates for present day, mass produced AFC systems.

² Calculated from: 160W/g_{Pt} given in the paper, a platinum price of \$18.95-\$20.68 and exchange rate of \$1.06-\$1.18/€ for the 60 days preceding the date of materials quote. (sources: www.platinum.matthey.com & www.oanda.com)

AFC Fuel Tolerance

The tolerance of AFC to carbon dioxide, found in reformed natural gas is shown in Table 6. The CO₂ tolerance is widely considered as one of the major hurdles for the technology to overcome, although many authors have challenged these opinions with their research into the field. The tolerance to other impurities in reformed natural gas was not available.

Substance	Quantity	Effect	Cell Type	Description
CO ₂	~400ppm	None		Hydrocell employs an amine based regenerative filter. Regenerated by periodic heating to release CO ₂ . ^{[18][note]}
CO ₂	0.1% 5%	50h life 5h life	Pt + fixed electrolyte	Rapid decay and cell death seen in platinum anode tests with a non-circulating electrolyte. ^{[13][expt]}
CO ₂	<100ppm ~400ppm	None None	Standard Pt Strongly bonded	CO ₂ will cause electrode pores to be blocked or mechanically damaged. Strongly bonded electrodes will however support unscrubbed air for many thousands of hours. ^{[19][expt]}
CO ₂	0.3-0.4%	<1% voltage loss	?	Reversible loss of performance. ^{[20][expt]}
CO ₂	1%	None	Ag	No significant effect on performance at 72°C. ^{[21][expt]}
CO ₂	4%	9% voltage loss	Ni/Ag	Reversible loss of performance. ^{[21][expt]}
CO ₂	5%	No degradation	DLR (Ni/Ag)	CO ₂ found to have no influence in degradation rate on strongly bonded, non-noble electrodes over several thousand hours. ^{[11, 12][expt]}

Table 6: Tolerance of AFC systems to fuel impurities.

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