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24.1 Introduction

The concept of using electrochemical reactions with polymer-based proton exchange membranes to separate, purify, and compress hydrogen was an unobvious outcome of the effort to develop power generation solutions for satellites and spacecraft in the United States in the 1950s. With the development of membrane-based fuel cell technology by General Electric in the 1960s and 1970s [1, 2], applications in hydrogen and related alkali ion-intensive processes [3] were a natural fallout of their programs. Included in the list of such applications besides fuel cells were the chlor-alkali membrane process, water electrolysis, oxygen concentrators, and electrochemical hydrogen pumping/concentrators (EHP). Furthermore, the development of Nafion[®] (registered trademark of DuPont) ion exchange membranes was also an outcome of this period and remains the primary membrane separator for all of the above applications to date though this is being challenged by a new class of materials

capitalizing on high-temperature membranes, the topic of this chapter.

Electrochemical hydrogen pumping was first reported by Maget [4] while developing the SPE (Solid Polymer Electrolyte, the original description of the membrane and electrode technology prior to “PEM” terminology) family of electrochemical processes. Specifically it was found that a proton generated during the oxidation of hydrogen at the anode would recombine into “new” molecular hydrogen at the cathode after the proton was driven through the membrane by an applied potential (Fig. 24.1). For this process to work, other reaction chemistries at the cathode had to be eliminated, e.g., the oxygen or halide reduction reactions. Though this was a unique application of hydrogen oxidation-reduction chemistry, the hydrogen pump process never materialized as a useful concept and remained an intellectual and academic curiosity until recently. Applications and concepts which have emerged include hydrogen pumping, hydrogen separations, as well as adiabatic hydrogen compression. It has only been in recent years that practical applications have been, or are now under development for industrial and alternative energy applications. Furthermore, this technique has been found to be a useful electrochemical analytical tool for studying electrode performance in such devices as fuel cells and water electrolyzers [5].

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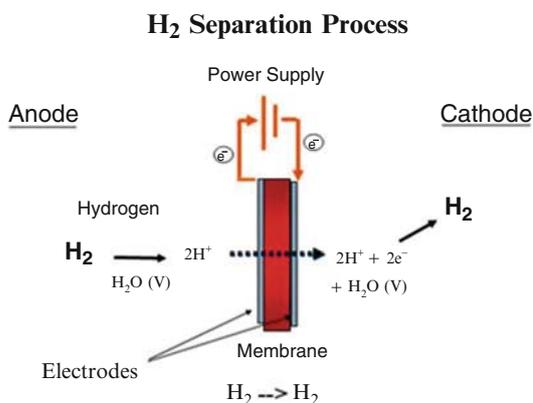
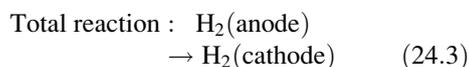
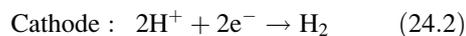
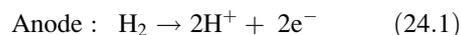


Fig. 24.1 Hydrogen membrane-based electrolysis

Recently, with the development of new high-temperature proton exchange membranes, as well as the increased interest in hydrogen-related technology and applications, there has been a resurgence of interest in EHP. Companies have formed to apply the process in both industrial and emerging hydrogen applications. There has also been an increase in the technical literature and conference presentations, and government (state and federal) agencies have included this technology in recent solicitations. These activities are partly due to membranes such as polybenzimidazoles (PBI), which have become available. This chapter will focus on the development of the high-temperature membrane-based electrochemical hydrogen pumping process.

24.2 Electrochemistry

The basic working principle of the electrochemical hydrogen pump process is that hydrogen molecules enter the anodic compartment of an electrochemical cell and are oxidized to protons and electrons within the catalyst layer of the electrode. The protons are driven through the ion exchange membrane while the electrons pass through the external circuit to the cathode as a result of the applied voltage to the electrodes. The protons and electrons then recombine at the cathode electrode to (re-)form molecular hydrogen. The overall chemical reactions are described by (24.1–24.3).



The cell voltage between the anode and cathode is given by (24.4). The Nernst potential E_{Nernst} is given by the Nernst equation (24.5), where E° is the standard potential of a hydrogen reaction, R is the gas constant, T is the temperature in Kelvin, F is Faraday's constant, p_{cathode} and p_{anode} are the partial pressures of hydrogen at the anode and cathode, respectively.

$$E = E_{\text{Nernst}} - E_{\text{polarization}} - E_{\text{ohmic}} \quad (24.4)$$

$$E_{\text{Nernst}} = E^\circ - \frac{RT}{2F} \ln \frac{p_{\text{cathode}}}{p_{\text{anode}}} \quad (24.5)$$

The polarization overpotential ($E_{\text{polarization}}$) is the sum of the polarization overpotentials at the anode and cathode and given by the Butler–Volmer equation. At low overpotentials, the polarization overpotential can be approximated by (24.6), where R is the gas constant, T is the temperature in Kelvin, F is the Faraday's constant, i is the current density, and i_0 is the exchange current density.

$$E_{\text{polarization}} = \frac{RT}{2F} \frac{i}{i_0} \quad (24.6)$$

The ohmic overpotential E_{ohmic} is the potential loss due to cell ohmic resistances and given by Ohm's law (24.7), where i is the current density, R_{ohmic} is the cell ohmic resistance, which includes membrane resistance, electrode resistance and cell hardware resistance.

$$E_{\text{ohmic}} = iR_{\text{ohmic}} \quad (24.7)$$

24.3 Low- and High-Temperature Devices

Just as the type of electrolyte membrane influences operational conditions and performance in fuel cells, the ion exchange membrane

used in hydrogen pumping applications affects the design and efficiency. Both low-temperature and high-temperature devices have been used or are under development for hydrogen separation and purification using this technique. In the low-temperature devices, the perfluorosulfonic acid family of membranes, e.g., Nafion[®], are ion exchange membranes with sulfonic acid groups directly bonded to the polymer. Devices containing these types of membranes operate at low temperatures (typically ~50–80 °C). Furthermore, the membranes need to be hydrated to support proton conduction [6]. A disadvantage of these membranes is the tendency of water to collect in the electrode layers and flow fields of the plates resulting in an undesirable “flooded” state. The result is a decrease in performance due to the reduced electrode active area. Among others, an additional disadvantage of the low-temperature cells is that the tolerance to selected impurities, e.g., carbon monoxide, at the electrode is low resulting in a (reversible) degradation process. This limits the utility of such devices in hydrogen separation and purification applications. Some of these obstacles in low-temperature devices can be overcome by using membranes that are able to operate at higher temperatures. Early high-temperature-based hydrogen purification was initially shown feasible using traditional phosphoric acid fuel cell (PAFC) technology [7]. High hydrogen recovery, high hydrogen purities, and tolerance to traditional fuel cell impurities were demonstrated using PAFC stack technology. In the 1990s, phosphoric acid-doped polymer membranes that offered similar increased tolerance to gas impurities were explored [8]. Operating at high temperatures (>100 °C) with phosphoric acid as the electrolyte requires a polymer membrane that is both thermally stable and chemically resistant. Since polybenzimidazoles (PBIs) demonstrate both of these qualities and have shown excellent stability under these conditions when used in fuel cells, PBI was a candidate for use in hydrogen pumping applications. Operating at these high temperatures also increases the platinum catalyst tolerance to carbon monoxide and other impurities, and thus becomes an enabling feature

in some applications. An additional advantage of high-temperature operation is that flooding of the electrodes with water is minimized, as water exists only in the gas phase at normal operating conditions. The chemistry of the polymer membrane influences the pump efficiency just as it influences the performance of a fuel cell. Various chemistries of PBI have been studied in hydrogen pumps to understand how the chemistry affects electrical efficiency, power consumption, durability of the membrane electrode assemblies, and gas purification.

24.4 High-Temperature Membrane Hydrogen Pumping

24.4.1 Para-PBI

Poly(2,2'-(*p*-phenylene)5,5'-bibenzimidazole) (para-PBI) has been tested by various research groups for high-temperature hydrogen pumping. In 2007, Perry et al. [9] reported the use of a para-PBI membrane prepared through the polyphosphoric acid process or PPA process [10] to be used as the polymer electrolyte membrane in an electrochemical hydrogen pump. Further information on the PPA process can be found in Chap. 10. Studies were performed using various gas mixtures, and operations were performed with and without external humidification in order to understand the power requirements, membrane electrode assembly (MEA) durability, and purification and electrochemical efficiencies. These para-PBI polymers had inherent viscosities (*IV*)s between 2.7 and 3.7 dL g⁻¹ and acid doping levels of 34.9–39.1 mol phosphoric acid (PA) per mole polymer repeat unit (PRU) [9]. Tests were initially performed with pure hydrogen and without external humidification at the anode. Polarization curves of the hydrogen pump are shown in Fig. 24.2.

The curves exhibited a linear relationship between voltage and current, which demonstrated reversibility, up to at least 1 A cm⁻². At a typical operating current density of 0.2 A cm⁻², electrochemical hydrogen pumping required relatively low voltages, i.e.,

Fig. 24.2 Polarization curves (scan rate 1.4 mA s^{-1}) of an electrochemical pump operating on pure hydrogen at $160 \text{ }^\circ\text{C}$, constant flow rate 94 mL min^{-1} . Reproduced from [9] with permission of Elsevier

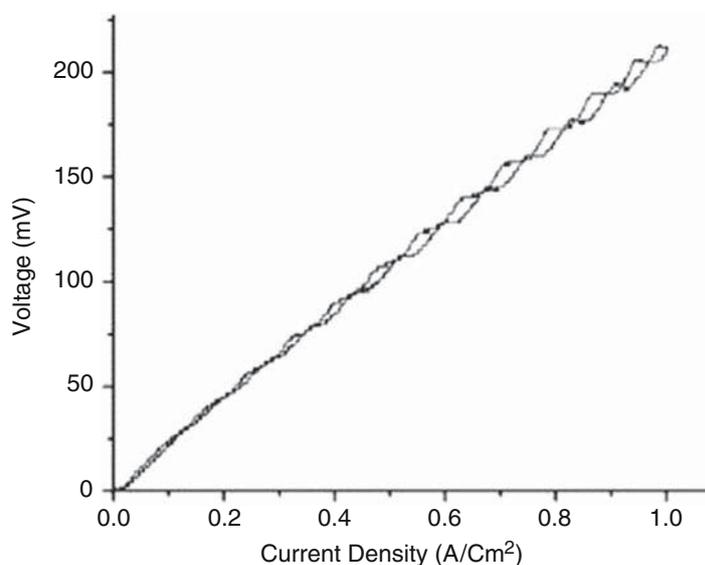
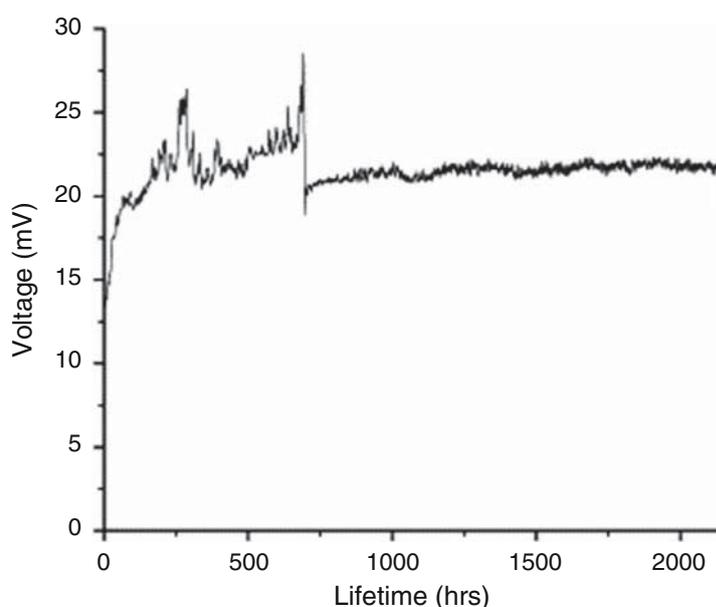


Fig. 24.3 Long-term operation of a hydrogen pump at 0.2 A cm^{-2} , 1.2 stoichiometric flow of pure hydrogen, $160 \text{ }^\circ\text{C}$. Reproduced from [9] with permission of Elsevier



45 mV at $160 \text{ }^\circ\text{C}$. The current efficiency of the electrochemical pump was conducted by measuring the cathodic outlet hydrogen flow at varying current densities. The relatively high current efficiencies, greater than 83 % from 0 to 2 A cm^{-2} , were achieved, showing high efficiencies under non-humidified conditions. The durability of the electrochemical pump was investigated at constant current density of

0.2 A cm^{-2} at $160 \text{ }^\circ\text{C}$ operating on pure hydrogen with no external humidification and the voltage was found to be relatively constant at 22 mV for over 2000 h of operation as shown in Fig. 24.3.

The effects of relative humidity were then studied by cycling the relative humidity between 0 and 3 % at $160 \text{ }^\circ\text{C}$. There were no large changes seen in the voltage by changing the relative

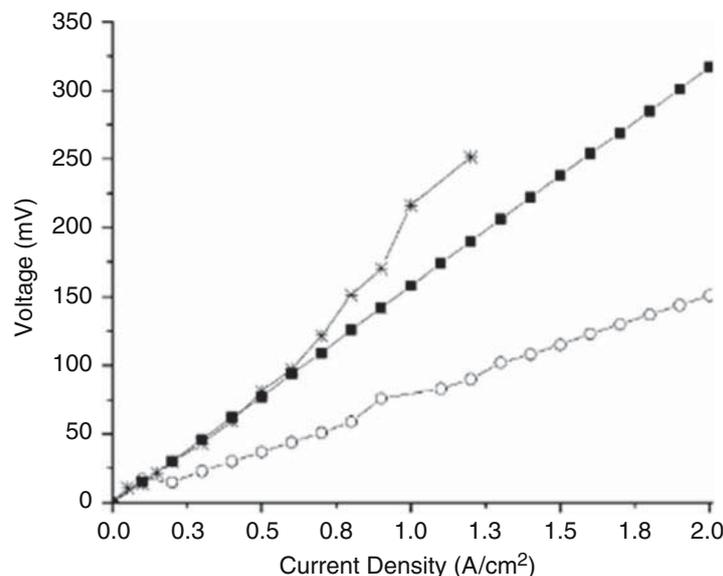


Fig. 24.4 Polarization curves for non-humidified conditions (*solid squares*) at 1653 h and humidified conditions (*unfilled squares*) at 2144 h. The crosshairs symbolize a humidified Nafion membrane operated at 70 °C for comparison [11]. The hydrogen inlet feed stream was adjusted to maintain 1.2 stoichiometric flows

at each current density for the humidified polarization curve. A constant flow of $\sim 75 \text{ mL min}^{-1}$ of hydrogen was supplied up to a current density of 0.8 A cm^{-2} and then the current steps were continued at 1.2 stoichiometric flow operation for the non-humidified polarization curve. Reproduced from [9] with permission of Elsevier

humidity; the average voltage for non-humidified conditions was approximately 33 mV and approximately 18 mV under humidified conditions. Performance was found to be improved at 3 % relative humidity when tested at 160 °C. This cell containing a para-PBI/PA membrane was reported to have a lifetime of over 4000 h with relatively stable voltages even under the stressful conditions of alternating between humidification and non-humidification. Power requirements were tested for both humidified systems and non-humidified systems by running polarization curves at 160 °C during each cycle. Figure 24.4 shows the polarization curves for the humidified and non-humidified operations and includes Nafion[®] (at 70 °C) for comparison.

It can be seen that both tests performed using para-PBI exhibit a near linear relationship. Voltages at 0.2 A cm^{-2} were 30 mV for the non-humidified cell and 18 mV for the humidified cell. Tests were also performed to evaluate the ability of the pump to run on gas streams contaminated with CO and CO₂ and to

evaluate the purity of the hydrogen produced at the cathode when operated at 160 °C. A gas stream of 35.8 % H₂, 11.9 % CO₂, 1906 ppm CO, and 11 % N₂ was used at the anode and the gas at the cathodic outlet was tested. Carbon monoxide concentrations were reduced to 11–13 ppm and carbon dioxide was reduced to 0.19–0.37 %, showing that these pumps can operate without high-purity hydrogen.

Kim et al. [12] later studied the effect of platinum catalyst loadings on the efficiencies of a H₂/CO₂ gas mixture (20/80 v/v) in cells containing membranes composed of para-PBI prepared through the PPA Process. Having the ability to reduce the amount of platinum used for catalysis in hydrogen pumping could significantly reduce material costs. Electrodes containing 1.1 and 0.2 mg cm⁻² were used at the anode and cathode to produce four different combinations of platinum loadings (1.1 mg cm⁻² at anode and cathode, 0.2 mg cm⁻² at anode and cathode, 1.1 mg cm⁻² at anode and 0.2 mg cm⁻² at cathode, and 0.2 mg cm⁻² at anode and

Fig. 24.5 Polarization curves for a hydrogen pump using different levels of Pt catalyst. (PHP = 1.1 mg cm^{-2} at anode and cathode, PHP-C = 1.1 mg cm^{-2} at anode and 0.2 mg cm^{-2} at cathode, PHP-A = 0.2 mg cm^{-2} at anode and 1.1 mg cm^{-2} at cathode, PHP-CA = 0.2 mg cm^{-2} at anode and cathode). H_2/CO_2 gas mixture (20/80 v/v). Reproduced from [12] with permission of Elsevier

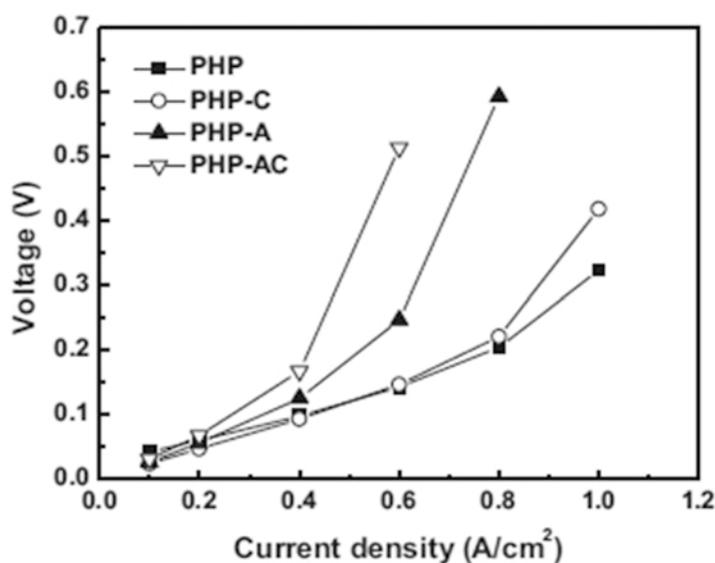


Table 24.1 Input and output of gases that were purified through hydrogen pumping using a Celtec-P membrane at 160°C

Gas	Input (%)	Output
H_2	50.5	99.896 %
CO	4.4	6.5 ppm
CO_2	39	1010 ppm
CH_4	6.1	18.7 ppm

1.1 mg cm^{-2} at cathode) to study the effect of the total platinum loading and the effect of a decrease in platinum loading at both the anode and cathode. Figure 24.5 shows the polarization curves of the various platinum loadings on the anodes and cathodes.

Compared to the MEA containing 1.1 mg cm^{-2} of platinum at both the anode and cathode, the MEA with lower platinum loading at the cathode (0.2 mg cm^{-2} at the cathode and 1.1 mg cm^{-2} at the anode) showed similar cell voltages up to 0.8 A cm^{-2} while the MEAs that contained lower platinum loading at the anode-side showed significantly higher cell voltages during H_2/CO_2 separation. These results indicate that the large overpotential seen in hydrogen purification using a H_2/CO_2 gas mixture is due mainly to the hydrogen oxidation reaction at the anode; therefore, the platinum loading at the cathode can be reduced without significant loss in performance.

Petek et al. [13] investigated a commercial Celtec-P-1000 MEA in a hydrogen pump at temperatures in the $120\text{--}180^\circ\text{C}$ range with detailed investigations at 150°C . They analyzed pumping characteristics using pure hydrogen, a simulated SMR-WGS (steam methane reforming-water gas shift) mixture of 70 % hydrogen, 3 % carbon monoxide, 20 % carbon dioxide, and 7 % methane, and a diluted hydrogen mixture containing as low as 5 % hydrogen. Hydrogen was separated quite efficiently from the SMR-WGS mixture with an estimated power requirement of 5 kW h kg^{-1} , which is much lower than the estimates for conventional PSA (pressure swing absorption) technologies. An adsorption limited current of approximately 0.3 A cm^{-2} was observed for the very dilute hydrogen containing mixtures with 5 % hydrogen.

H2Pump LLC tested various gas mixtures in a hydrogen pump with a Celtec-P membrane [14]. When using a gas mixture containing 50.5 % H_2 , 4.4 % CO, 39 % CO_2 , and 6.1 % CH_4 at 160°C , hydrogen was able to be purified to almost 99.9 % (Table 24.1).

Further testing was performed on a gas mixture containing 1.12 % CO, 43.8 % CO_2 , with a H_2 balance using a Celtec-P membrane at 160°C at 0.2 A cm^{-2} . The carbon monoxide was found to be ~ 1 ppm at the outlet. These findings show

Fig. 24.6 Purification ratios for carbon dioxide and carbon monoxide at various current densities using a Celtec-P membrane at 160 °C

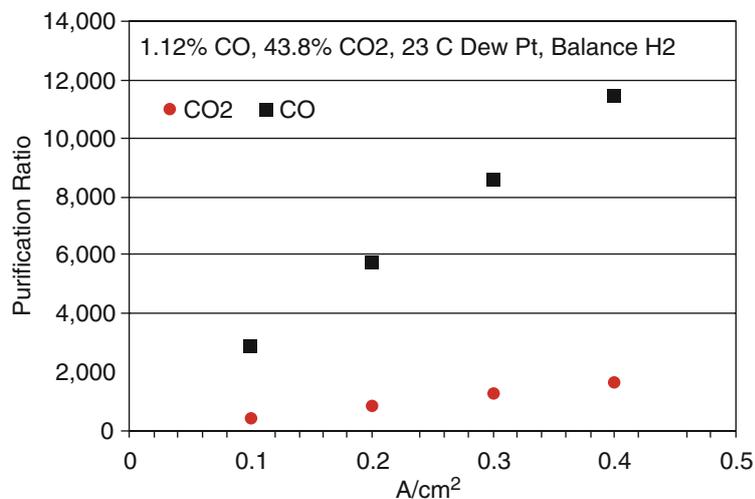
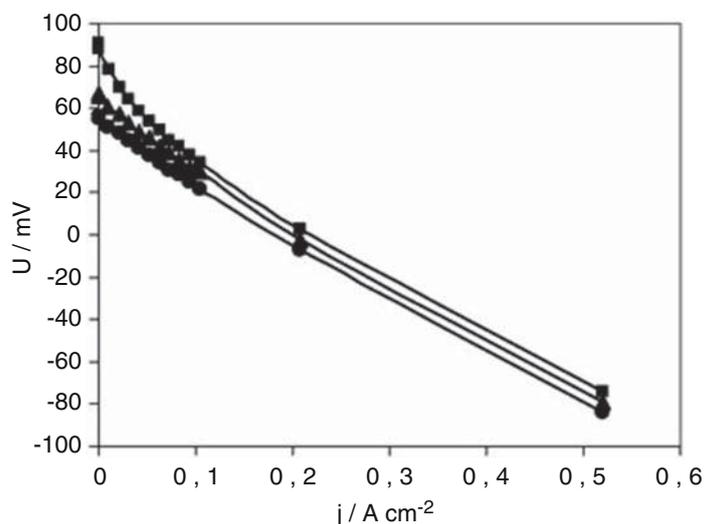


Fig. 24.7 Polarization curves measured at 160 °C for changing cathode gas pressures (*square* = 0 bar, *triangle* = 90 mbar, *circle* = 120 mbar) Reproduced from [5] with permission of Elsevier



the excellent purity that can be achieved using a para-PBI membrane in a hydrogen pumping device (Fig. 24.6).

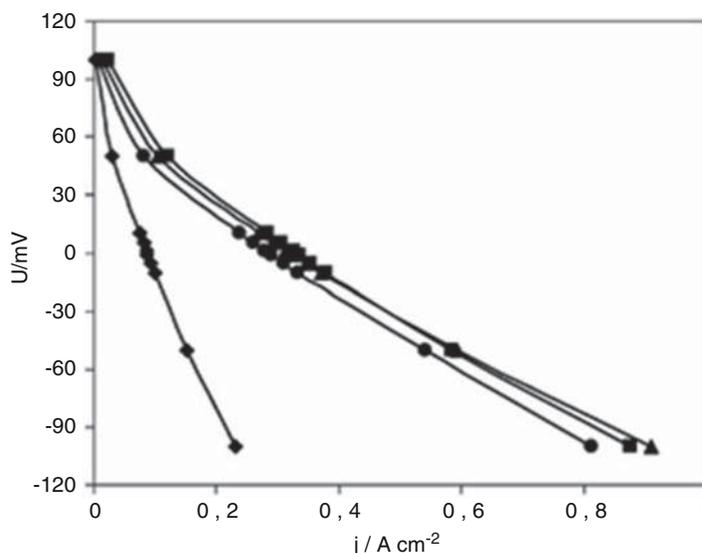
24.4.2 Other PBIs

Huth et al. [5] performed hydrogen pumping tests on a PBI membrane to study proton transport and anode kinetics. Unfortunately, the source of the material, type of PBI, and membrane acid doping level were not specified. Polarization curves can be seen in Fig. 24.7 and showed a nearly linear behavior over the entire potential range

indicating that membrane resistance dominates the overall cell resistance in this region.

The effects of temperature when the partial pressure of hydrogen was held at 3 bar were studied. When temperature increased, a larger change in current was seen with changing voltage showing an increase in conductivity (Fig. 24.8). Huth et al. [5] went on to perform many further experiments to study the proton transport mechanism and anode kinetics and found that the anodic hydrogen oxidation reaction follows the Volmer–Tafel mechanism with the Volmer reaction being the rate-limiting step.

Fig. 24.8 Polarization curves of the proton pump at various temperatures with a hydrogen partial pressure of 3 bar (*diamond* = 40 °C, *circle* = 80 °C, *triangle* = 120 °C, *square* = 160 °C). Reproduced from [5] with permission of Elsevier



Thomassen et al. [15] also evaluated a PBI-based membrane for EHP applications. Again, the membrane source, type of PBI, and membrane acid doping were not specified. Reformate gas mixtures containing varying amounts of hydrogen, carbon dioxide, carbon monoxide, nitrogen, and methane were used in a hydrogen pump cell with good results. Current efficiencies up to 90 % were reported at high current densities, and the cells were operated at a differential pressure of 0.65 bar. Significant reductions in gas impurities were measured under stable operating conditions.

24.5 Low-Temperature Hydrogen Pumping

Although the focus of this book is predominantly on polymer membranes for use in high-temperature devices, a few examples of polymer membranes used in low-temperature hydrogen pumping have been included in this chapter for comparison.

24.5.1 Perfluorosulfonic Acid-Based Membranes

Perfluorosulfonic acid-based membranes are some of the most commonly studied membranes in hydrogen pumping. Lee et al. [16] studied

hydrogen purification at low temperatures using a Nafion[®] 115 membrane using a hydrogen/nitrogen/carbon dioxide mixture. Testing was performed at various temperatures and operating pressures with hydrogen inlet compositions ranging from 10 to 90 %. Detailed results from a 50 % hydrogen mixture are shown in Fig. 24.9. Hydrogen purity was then measured as a function of current density when testing was performed at various temperatures (Fig. 24.10).

As expected, hydrogen purity increased with increasing current density. Hydrogen purities of >90 % were easily achieved at a wide range of temperatures, pressures, and current densities. Abdulla et al. [17] conducted an excellent and detailed study on the efficiency of hydrogen pumping using a Nafion[®] 115 membrane in both a single stage and multistage design. Further studies on perfluorosulfonic acid-based membranes can be found in the additional references [11, 18–21].

24.5.2 Poly(Ether Ether Ketone)-Based Membranes

Poly(ether ether ketone)-based membranes (PEEK) have also been studied in low-temperature hydrogen pumping as more cost effective alternatives to perfluorosulfonic

Fig. 24.9 Polarization curves for various cell temperatures and pressures (hydrogen inlet composition 50 %)
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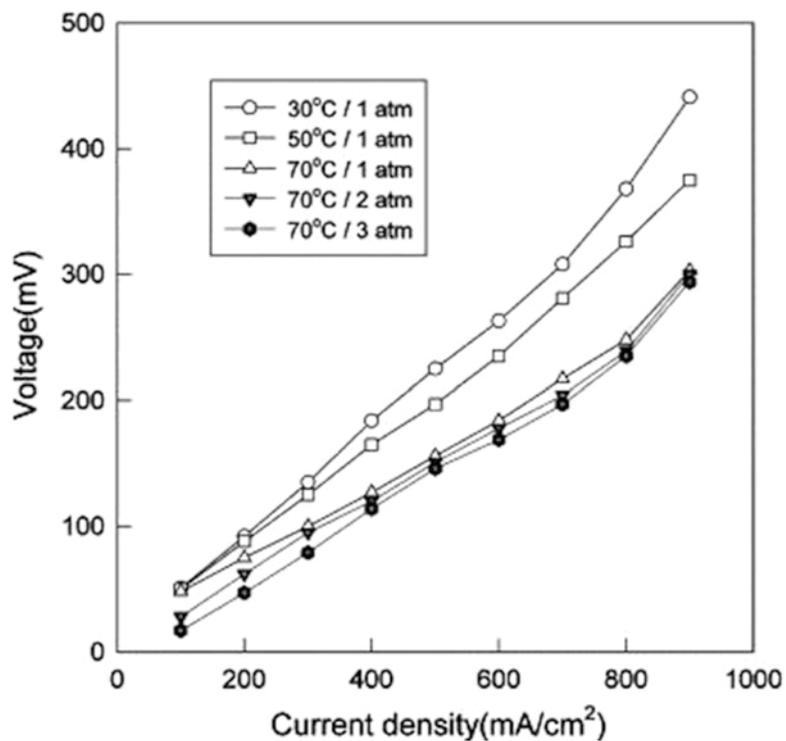


Fig. 24.10 Hydrogen purity vs. current density at various cell temperatures and operating pressures (hydrogen inlet composition 50 %).
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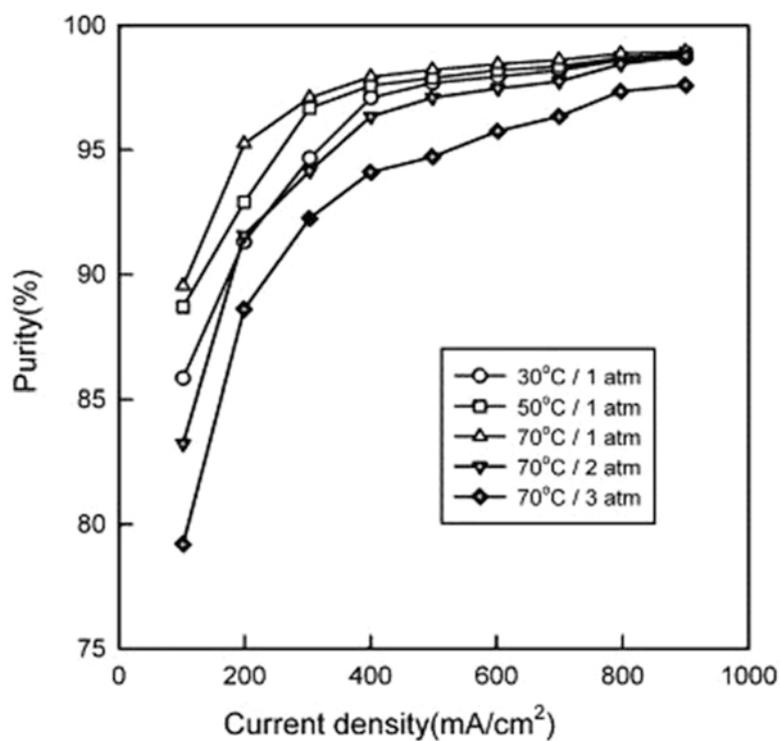
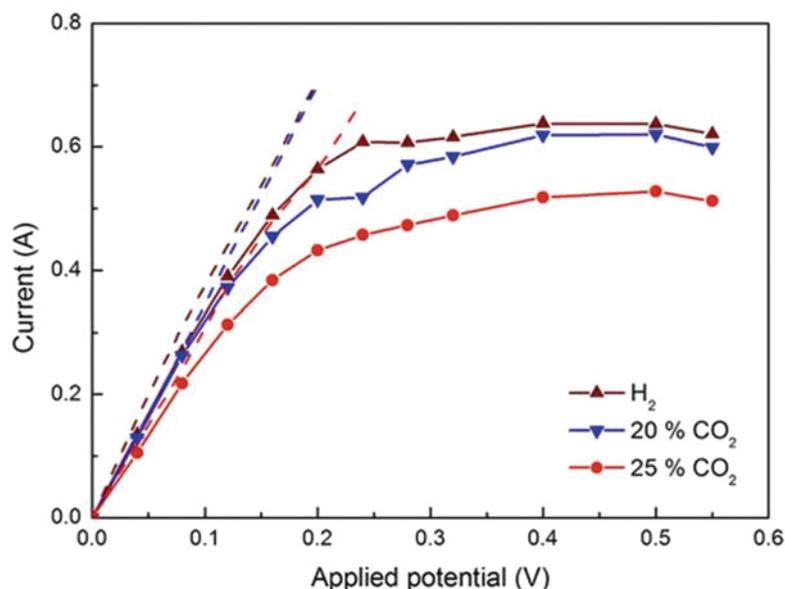


Fig. 24.11 Current as a function of applied potential with varying amounts of CO₂ at 80 °C and 16 mL inlet. Reproduced from [16] with permission of the American Chemical Society



acid-based membranes. Wu et al. [22] synthesized a sulfonated PEEK (SPEEK) membrane with a semi-interpenetrating network of cross-linked polystyrene sulfonic acid (sIPN) and performed hydrogen pumping tests. Current was measured as a function of applied potential at varying CO₂ levels (Fig. 24.11). It can be seen that the current quickly increases until the limiting current is reached which was indicative of a mass transport resistance. Polarization curves for the sIPN membrane with various anode feeds can be seen in Fig. 24.12 (active area 1.9 cm⁻²).

24.6 Applications

The application of electrochemical hydrogen pumping technology is relatively recent and has been predominately limited to four areas: (1) industrial hydrogen recycling, (2) fuel cell applications (anode tail-gas recirculation for reuse in fuel cells or related fuel cell systems), (3) electroanalytical methods, and (4) hydrogen compression. Of the four, only the first three topic areas have seen significant development efforts although electrochemical compression is experiencing a higher degree of R&D activity due to the current interest in hydrogen vehicle

refueling. Developed in the 1960s, the use of this technology has been slow to emerge. This is partly due to the fact that the EHP stack technology parallels fuel cell development and commercialization activities.

24.6.1 Electrochemical Industrial Hydrogen Recycling

The recycling of hydrogen using electrochemical methods in industrial applications has been a recent focus of a number of companies, the most predominant one being H2Pump LLC (Latham, NY) [23]. In this application, hydrogen is recovered from hydrogen-intensive industrial processes, purified, and then made available for reuse on-site. Applications include metallurgical processes such as stainless steel annealing, brazing, powder metal sintering, as well as semiconductor production, to name a few. Chemical processes that generate hydrogen are also opportunities for this technology. There are a number of challenges that must be overcome if EHP methods are to be realized in industrial settings. Regardless of the stack technology, it must be scalable to be able to handle large volumes of process gas, able to operate reliably

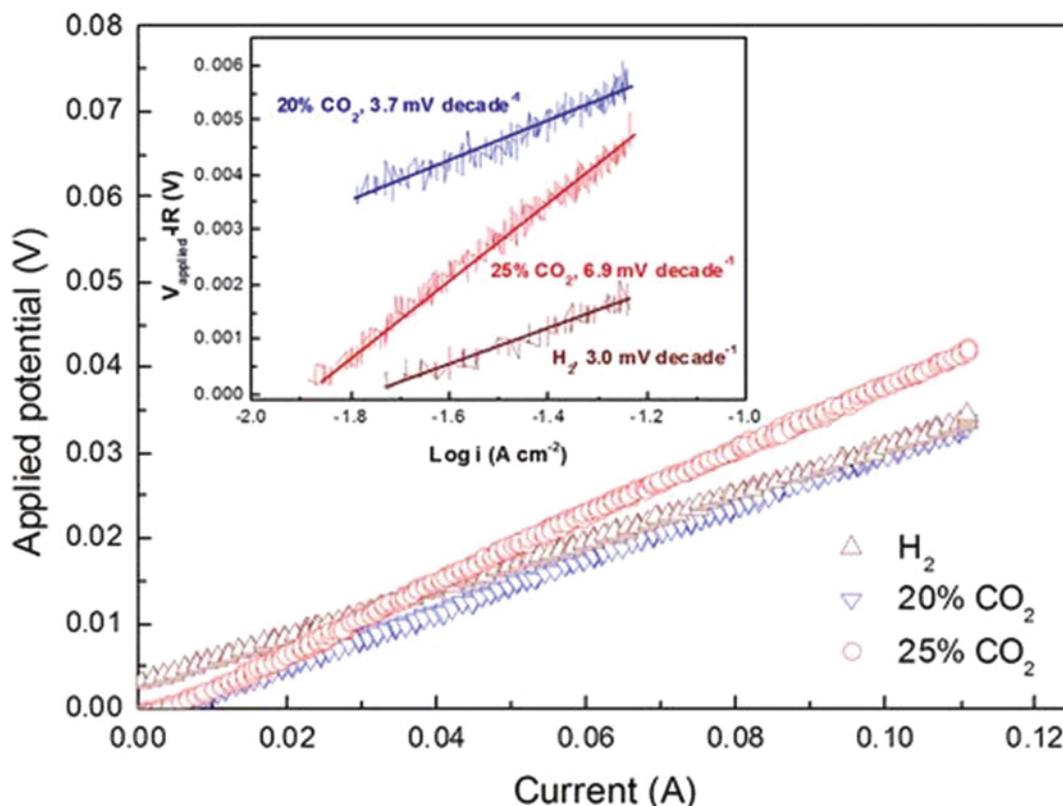


Fig. 24.12 Polarization curve and Tafel Plots. Reproduced from [22] with permission of the American Chemical Society

in the presence of a host of impurities from the industrial process, and be able to generate pressurized product hydrogen. The pressure requirement to drive the “pumped” hydrogen through a final clean up stage, typically a dryer, as well as to feed it back into the feedstock manifold of the site. As a result, a “system” to manage the different unit operations is required as a function of the operating profile of a given application. Such systems have been developed and Fig. 24.13 shows a fully integrated unit that is capable of pumping 100 kg of hydrogen per day.

24.6.2 Fuel Cell Applications

There are two potential uses of an EHP in combination with fuel cells. In the first, anode tail-gas recirculation, hydrogen is extracted from the fuel

cell stack anode exhaust. Once recovered, it is then fed back to the original source of the hydrogen thereby improving the overall fuel efficiency of the system. In the second, excess hydrogen from the reformer is captured and recovered for either recirculation or for use in other fuel cell subsystems. In addition, recovered hydrogen from either of these two sources within fuel cell systems can be used for its heating or chemical value, or for providing a source of hydrogen for motive refueling needs. Hydrogen pumps have been used by Bloom Energy Corporation to reach technological and cost goals in planar solid oxide fuel cells (PSOFC). In this application, a hydrogen pump can be used for hydrogen recycling or external hydrogen delivery. The hydrogen pump test duration lasted 2000 h and showed less than a 5 % performance degradation on hydrogen production [24].



Fig. 24.13 H2Pump LLC hydrogen pumping unit

24.6.3 Electroanalytical Methods

With a strong emphasis on the development of electrochemical membrane processes, e.g., water electrolysis and fuel cells, electrode performance must be well characterized electrochemically. Use of a hydrogen pump concept can provide insight into anode and/or cathode electrode electrochemical characteristics. Furthermore, the method can also be utilized to determine the back diffusion of hydrogen through the membrane [5, 25].

24.6.4 Compression

EHP technology is of interest as it can be used in place of a mechanical compressor to generate pressurized hydrogen. Although it is membrane and hardware dependent, very high pressures have been reported using EHP technology, at least at the lab scale. The advantages include (1) energy is consumed only to compress

hydrogen, (2) unlike a mechanical compressor, a pressure head is not required, (3) the capital costs of the core EHP system are lower than mechanical methods, (4) high turn down ratio characteristics, and (5) the energy requirements are comparable to the mechanical compressor as measured by the kW h kg^{-1} of hydrogen which is pumped and compressed. A significant development challenge includes managing high differential pressures across the membrane, thereby requiring sufficient mechanical strength of the membrane separators, gaskets, and related stack hardware. In addition, the forces encountered on the end-plates of a stack can be significant. Due to the logarithmic nature of the Nernst potential, the energy requirements are approximately $6\text{--}10 \text{ kW h kg}^{-1}$, similar to that required by a mechanical compressor. Pressures in the vicinity of 345 bar have been recently reported [26] for Nafion[®] membrane systems whereas 22 bar has been reported for PBI high-temperature membrane pumps [14].

24.6.5 Hydrogen Purification

Regardless of the source of the hydrogen, the technique can be used for bulk purification of hydrogen as long as the impurities that have to be removed from the hydrogen do not impact the electrochemical membrane process or the ancillary subsystems.

24.6.6 Limitations of the Technology

There are a number of limitations of this technology which also indicates opportunities for further development. These are presented in Table 24.2.

24.6.7 Comparison to Fuel Cells: Lifetime/MEA Stability

Although the electrochemical pump stack module is similar to stacks used in membrane fuel cells, there are significant differences. These include the future prospect of not having to use

Table 24.2 Technological limitations

Metric	Impact	Consequences
Performance	Electrode stability	Decreased performance and/or higher energy requirements
	Membrane and electrode poisoning	Reliability
	Low anode hydrogen concentrations	
	Membrane flooding and/or drying	
Pressure limitation	Membrane and hardware mechanical stability	Catastrophic failure
Cost	Utilization of precious metals	Economics
	Membranes	

precious metals, lower catalyst loadings, different flow fields, the lack of oxygen in the cathode, and low voltages for the hydrogen oxidation and reduction processes. The latter two are of great importance as the primary degradation mechanism in low-temperature membrane fuel cells is related to hydrogen peroxide radical attack of the membrane and ionomer in the electrode layers. The lack of oxygen in an EHP process creates distinct lifetime and performance advantages over fuel cells. Furthermore, as the voltages required to “drive” the oxidation and reduction reactions are by definition zero (except for a small overvoltage), the carbon supports of the catalysts are not at risk of oxidation.

24.7 Conclusions

High-temperature hydrogen separation using PBI-based membranes has been demonstrated to produce high purity hydrogen, even without significant optimization of the cell design, gasketing, and sealing strategies. A particular advantage of high-temperature operation is the increased tolerance to impurities that may be present in reformation processes or in industrial process streams. This is a critical aspect of high-temperature EHP and expands the utility of such devices for practical applications. Early work in this field has confirmed the scalability of the device to industrially relevant volumes with power requirements that are considerably lower than widely used existing technologies. Further development of devices with higher purity gas

production and higher pressures will be assisted by additional hardware designs. It is expected that longer lifetimes will be realized as compared to fuel cells by the removal of the oxidative degradation processes found in fuel cell cathodes. There appear to be many opportunities for membrane development, as well as, stack and system designs that are tailored to meet the needs of both current industrial and future hydrogen markets.

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