Chapter 44
Catalyst coated composite membranes

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1 INTRODUCTION

The benefit of mechanical reinforcement of ionic membranes was realized early in the development and application of perfluoro ionomers for industrial electrolytic processes, such as chlor-alkali in the late 1970s.[1] Free-standing, pure, ionomeric films are typically weak and susceptible to swelling when hydrated; hydration of the membrane significantly reduces its strength due to the plasticization of the ionomer. The macro-mechanical reinforcement of ionomer membranes for industrial applications is today typically performed with inert chemically resistant woven fabrics, such as woven polytetrafluoroethylene (PTFE). This provides the desired physical strehgth and allows thinner membranes with lower resistance to be utilized, with the further benefit of decreasing material content, and therefore, cost of the membrane.

Woven reinforcements or macro reinforcements are currently on the order of millimeters in thickness and are consequently now regarded as orders of magnitude too thick for state-of-the-art polymer electrolyte membrane fuel cell (PEMFC) applications. In 1995, W. L. Gore & Associates, Inc. (Gore) introduced the Gore-Select® membrane, a new micro reinforced composite expanded polytetrafluoroethylene (ePTFE) polymer electrolyte membrane technology[2–4] targeted specifically toward PEMFC applications. Gore was able to create structures considerably thinner than traditional reinforced industrial membranes by utilizing a microporous ePTFE membrane for support, rather than a woven, fabric-type, reinforcement. The micro-reinforcement allows Gore-Select® membranes to utilize ionomers that do not have sufficient mechanical properties (i.e., ionomers of equivalent weight (EW) less than 1000) to be used as thin film membranes in practical applications. As a result, the benefits of improved strength and lower resistance that have been valuable to industrial applications can now be achieved in fuel cell applications. Gore-Select® membranes have been demonstrated in fuel cells at thickness as low as 5 μm.[2]

In order to realize the benefits of thin composite membranes, new types of high performance electrode structures and membrane electrode assembly (MEA) manufacturing techniques needed to be developed, that were compatible with these unique membranes. The Primea® Series MEA, based on the Gore-Select® membrane, was also first introduced in 1995. Several MEA series have now been developed by Gore and demonstrated widely in all PEMFC applications.[5–8]

2 THE MICRO REINFORCED COMPOSITE GORE-SELECT® MEMBRANE

Prior to the introduction of the ePTFE micro reinforced composite perfluoro sulfonic acid Gore-Select® membrane, the practical membrane thickness and choice of ionomers used for PEMFC membranes were dictated by the poor mechanical properties of ionomer membrane films. The ability to micro reinforce ionomer films provides numerous physical and mechanical benefits for PEMFCs. Some of these characteristics have been previously reviewed early in Gore-Select® membrane development.[2]

Handbook of Fuel Cells – Fundamentals, Technology and Applications, Edited by Wolf Vielstich, Hubert A. Gasteiger, Arnold Lamm.
Volume 3: *Fuel Cell Technology and Applications*. ISBN: 0-471-49926-9.

The reinforced composite nature of the membrane imparts significant x-y dimensional stability upon hydration (Figure 1). This is important when considering the tolerance requirements necessary in MEA manufacturing for reliable and convenient fuel cell stack assembly: there are numerous stack failure mechanisms which can be attributed to poor stack assembly tolerances. Membrane dimensional stability may also be important in achieving a durable membrane-electrode interface for the MEA, especially in dynamic use, in which cyclic swelling of the ionomer is expected. The results (Figure 1) demonstrate Gore-Select® membrane to be quite isotropic in nature (similar dimensional changes in machine and transverse directions); the extruded, nonreinforced membrane is, however, anisotropic and was observed to swell considerably in the transverse direction. The anisotropic nature of the extruded film may result in considerable stresses in the membrane in application, leading to mechanical failures. The slight shrinkage measured in the machine direction on water boiling was reproduced in all samples tested, either in the as-received or heat-treated forms.

There are many possible membrane mechanical properties that could be considered when designing PEMFC membranes, such as tensile strength.[2] One of the most important criteria in identifying a practical membrane material for MEA manufacturing and membrane service is tear strength or tear resistance. Figure 2 compares the stress required to propagate a membrane tear in thin reinforced Gore-Select® membrane and nonreinforced Nafion® 112 membrane using American Society for Testing and Materials (ASTM) test 1922–94a. The results indicate that both membrane types are anisotropic and have greater tear resistance in the machine direction, and both membrane types also have reduced tear resistance when hydrated. However, Gore-Select® membrane shows superior tear resistant properties to Nafion® 112 membrane. Even the hydrated transverse direction for the Gore-Select® membrane is more tear resistant than the dry transverse direction for Nafion® 112 membranes.

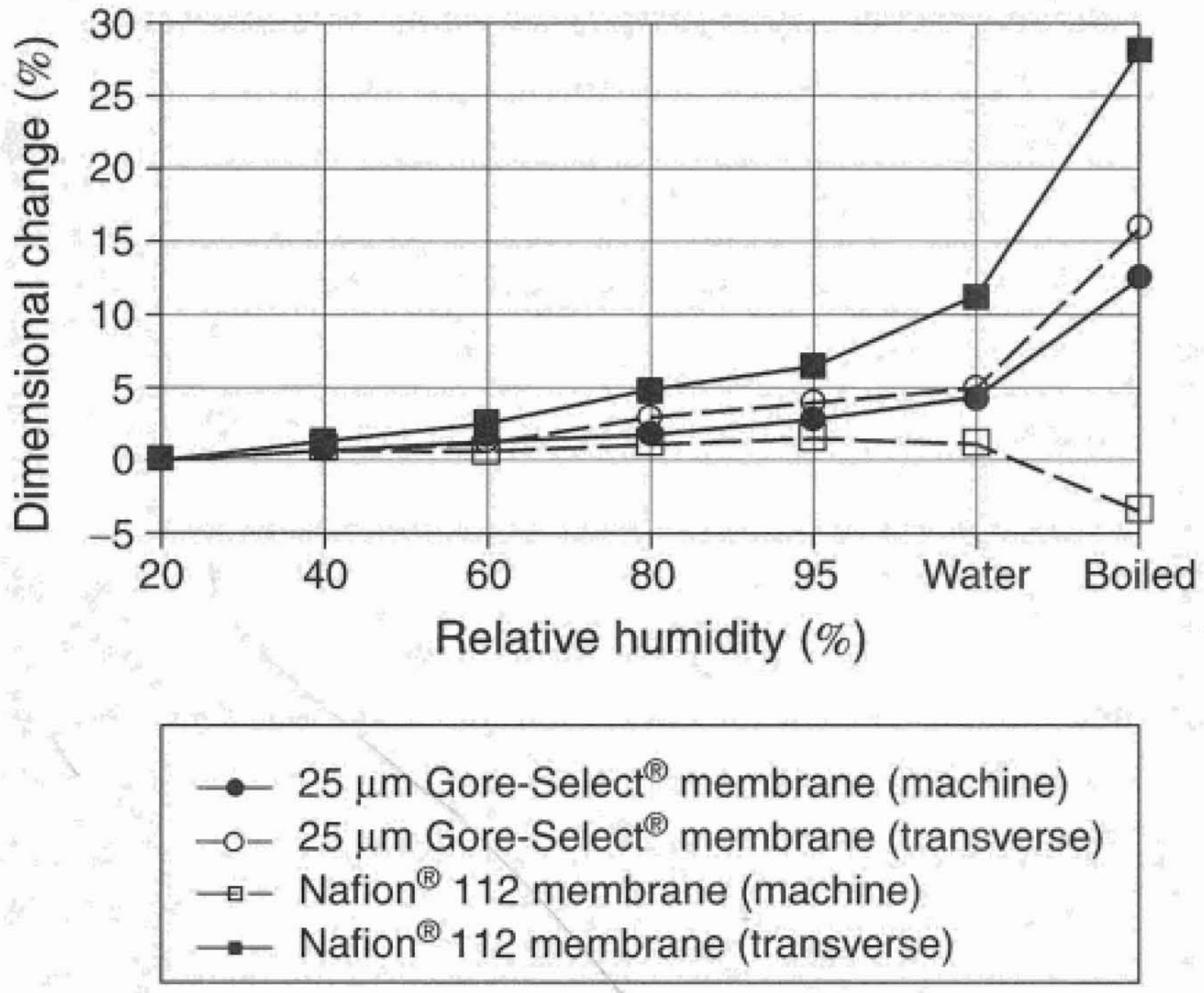

Figure 1. Comparison of dimensional stability of Gore-Select® membranes (25 μm) and Nafion® 112 membranes (50 μm) as a function of relative humidity (20–95% relative humidity (RH)), in contact with water at ambient temperature and after boiling in water for approximately 30 min. Dimensional changes are referenced to 20% RH at ambient temperature.

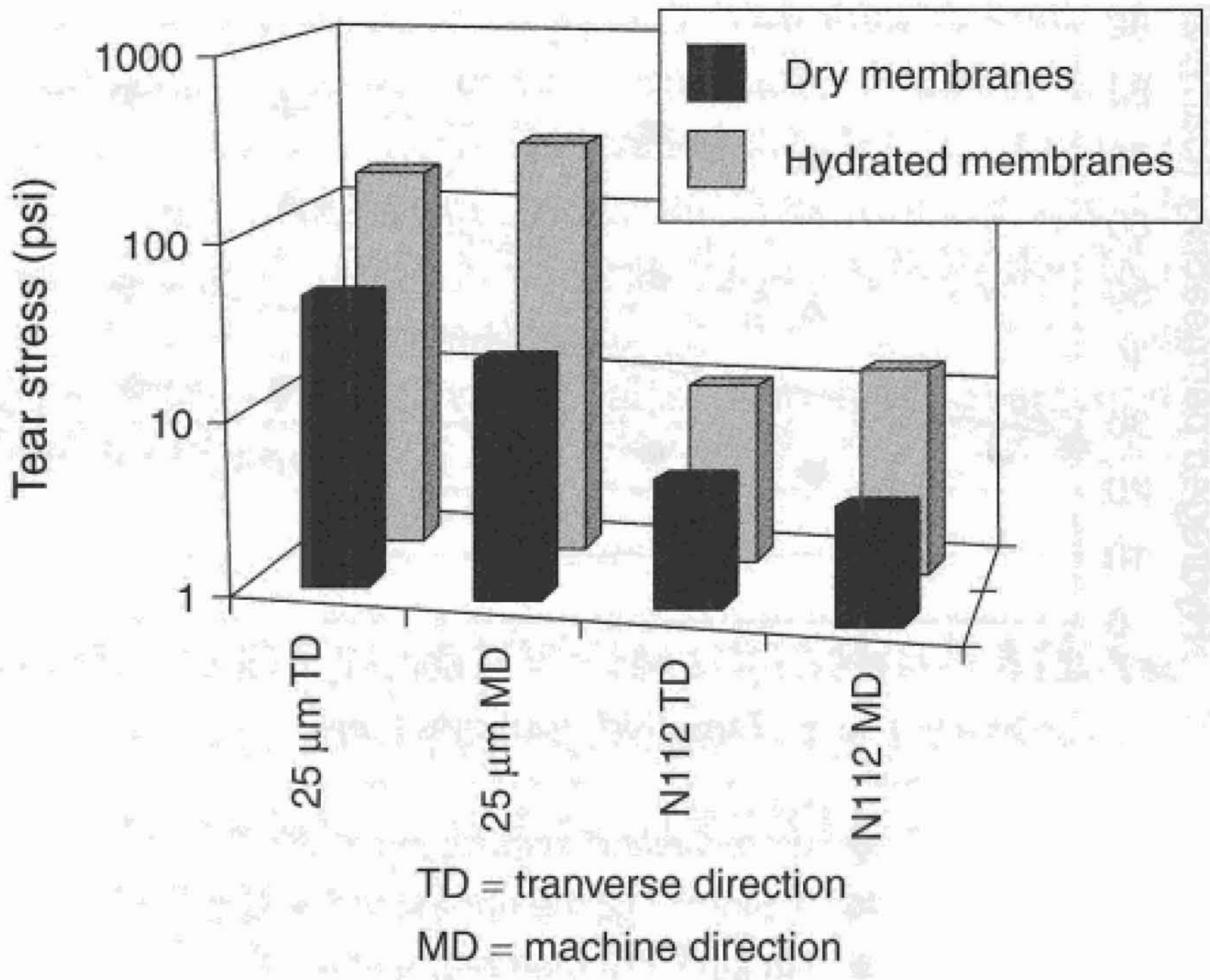

Figure 2. Comparison of tear strength for hydrated and dry Gore-Select® membrane (25 μm) and Nafion® 112 membrane in machine and transverse directions.

Understanding reactant (especially hydrogen) permeability through thin membranes is of vital importance from the perspective of fuel efficiency, high voltage efficiency, and should also be considered in understanding membrane durability. Membrane permeability is commonly measured at Gore by two techniques:

(a) Permeation cell method. A membrane is used to divide two compartments of a permeation cell, one flowing hydrogen and the other flowing nitrogen, a carrier gas. Hydrogen permeating through the membrane is transported by the carrier gas to a gas chromatographic detector. This method allows very accurate control of temperature and relative humidity. The results (Figure 3), consistent with those obtained by Broka *et al.*,[9] demonstrate that hydrogen permeability for Nafion® 112 increases as a function of temperature and relative humidity. Gore-Select® membranes follow the same trends as Nafion® 112 at 80 °C with respect to relative humidity. The presence of the membrane reinforcement slightly decreases the permeability of the membrane, as one might predict,

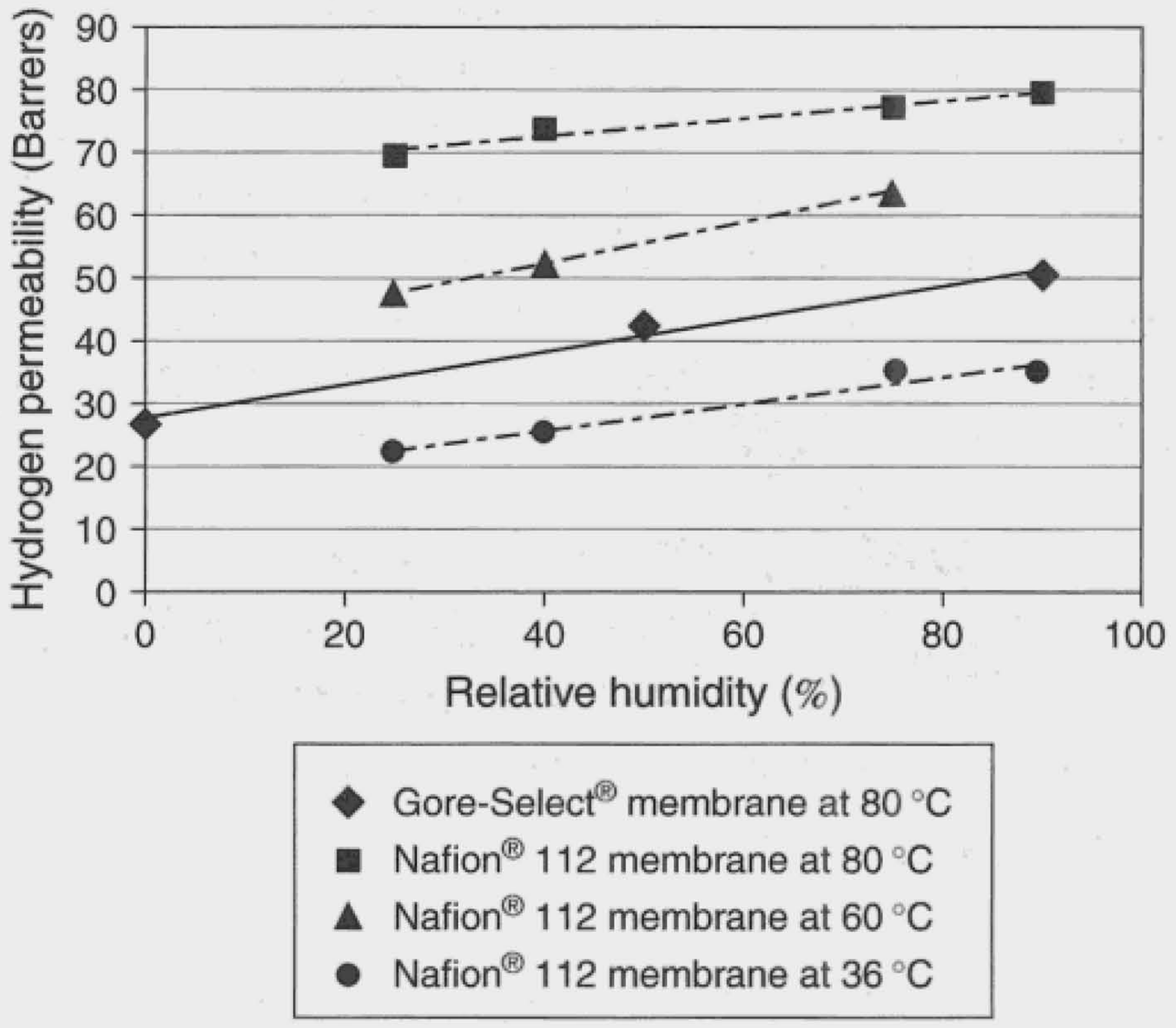

Figure 3. Comparison of hydrogen permeability as a function of measurement relative humidity for Gore-Select® membrane (25 μm) and Nafion® 112 membrane measured at different temperatures (1 Barrer = 10^{-10} cm^3(standard temperature and pressure (STP)) cm s^{-2} cm^{-2} cm[Hg]).

due to the incorporation of the impermeable ePTFE matrix with its associated increased gas tortuosity.

(b) Electrochemical method (performed in the fuel cell hardware). The fuel cell hardware is operated with hydrogen on one side of the membrane and nitrogen on the other. A potential is applied across the cell, so that hydrogen permeating through the membrane is oxidized electrochemically. Membrane permeability is determined from the limiting current density for hydrogen oxidation. A similar technique is published for measuring methanol permeability[10] and provides a very useful in-situ method (for more details see **Principles of MEA preparation**, Volume 3). Figure 4 reports results of measurements using this technique for a 25 μm Gore-Select® membrane as a function of temperature and pressure. Considering the errors associated with the two techniques, a difference of 30% between the permeation and electrochemical measurements is very reasonable. [Note: 1 mA cm^{-2} of hydrogen crossover is equivalent to 38 Barrers for a 25 μm membrane at 101 kPa (76 cm Hg) and 19 Barrers for 50 μm membranes at 101 kPa (76 cm Hg)].

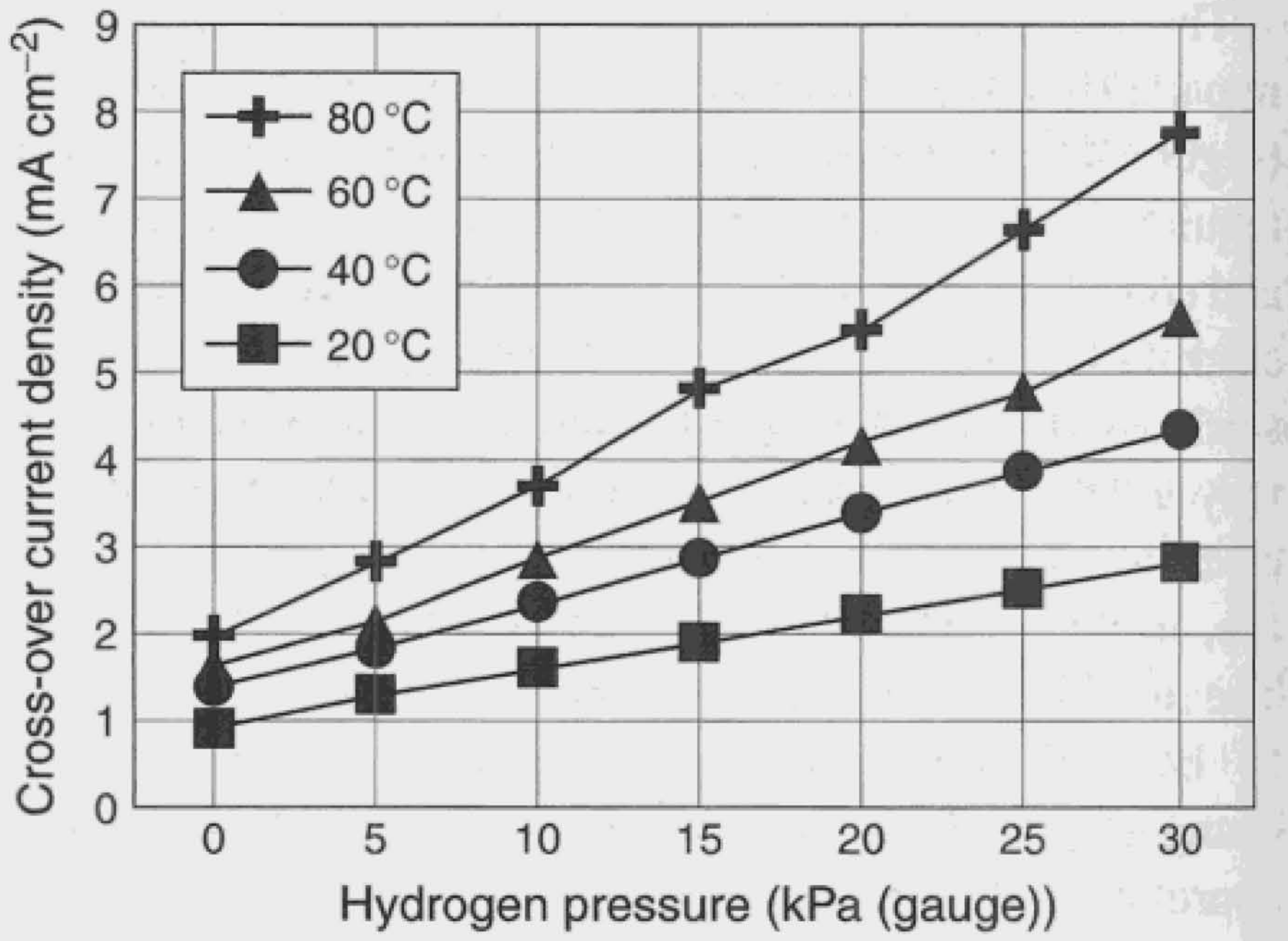

Figure 4. Hydrogen crossover current density as a function of temperature and pressure for a Gore-Select® membrane (25 μm) measured by the electrochemical technique at 100% relative humidity.

A key benefit of thin membranes is their increased ionic conductance. The through-plane (z direction) membrane ionic conductance has been measured for a 25 μm Gore-Select® membrane and Nafion® 112 membrane as a function of temperature and relative humidity, by a two-point probe, high frequency impedance technique.[11] To simulate operating fuel cell conditions, the membrane was compressed to a 1034 kPa during the measurement.

Plotting conductance, K, as a function of relative humidity x between 20 and 100% at 80 °C (Figure 5) for 25 μm Gore-Select® membrane and Nafion® 112 membrane, a power law relationship can be derived: $K = A \times x^b$, where coefficient A and exponent b are fitted parameters. A

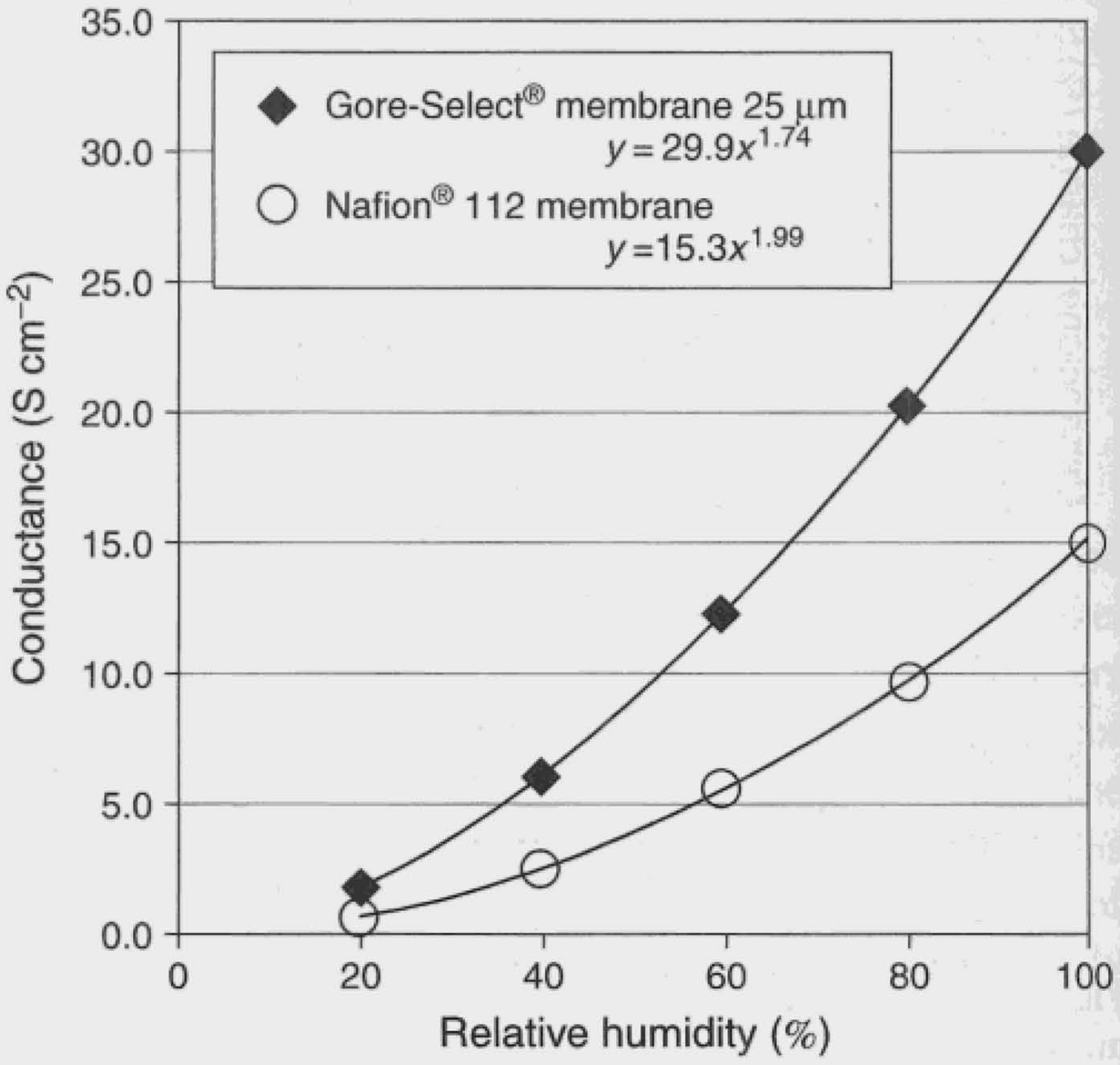

Figure 5. Through plane (z direction) conductance as a function of relative humidity at 80 °C for a Gore-Select® membrane (25 μm) and Nafion® 112 membrane.

determines the maximum achievable membrane conductance when fully saturated at 100% relative humidity; the values obtained are in agreement with previously published data.[12, 13] The exponent b describes how fast the conductance of the membrane decreases as relative humidity is reduced. 25 μm Gore-Select® membrane exhibits much higher A and lower b when compared with a Nafion® 112 membrane, which means that the composite membrane provides both higher conductance in the fully hydrated condition, and loses conductance at a slower rate than the Nafion® 112 as relative humidity is decreased.

The relative conductivities of the two different membranes (σ_{GS} and σ_{N}) can be better compared by combining their power law relationships (from Figure 5).

$$\frac{\sigma_{\mathrm{GS}}}{\sigma_{\mathrm{N}}} = \frac{A_{\mathrm{GS}}}{A_{\mathrm{N}}}\frac{25}{50}x^{(b_{\mathrm{GS}}-b_{\mathrm{N}})} \tag{1}$$

$$\frac{\sigma_{\mathrm{GS}}}{\sigma_{\mathrm{N}}} = 0.98x^{-0.25} \tag{2}$$

This illustrates that 25 μm Gore-Select® membrane has the same conductivity as Nafion® 112 membrane at 100% relative humidity. The high conductivity of the Gore-Select® membrane with the incorporation of a nonconductive matrix is achieved by using ionomers of less than 1000 EW. The advantage of incorporating low EW ionomer in the Gore-Select® membrane is further demonstrated in the superior conductivity of this membrane as relative humidity is reduced.

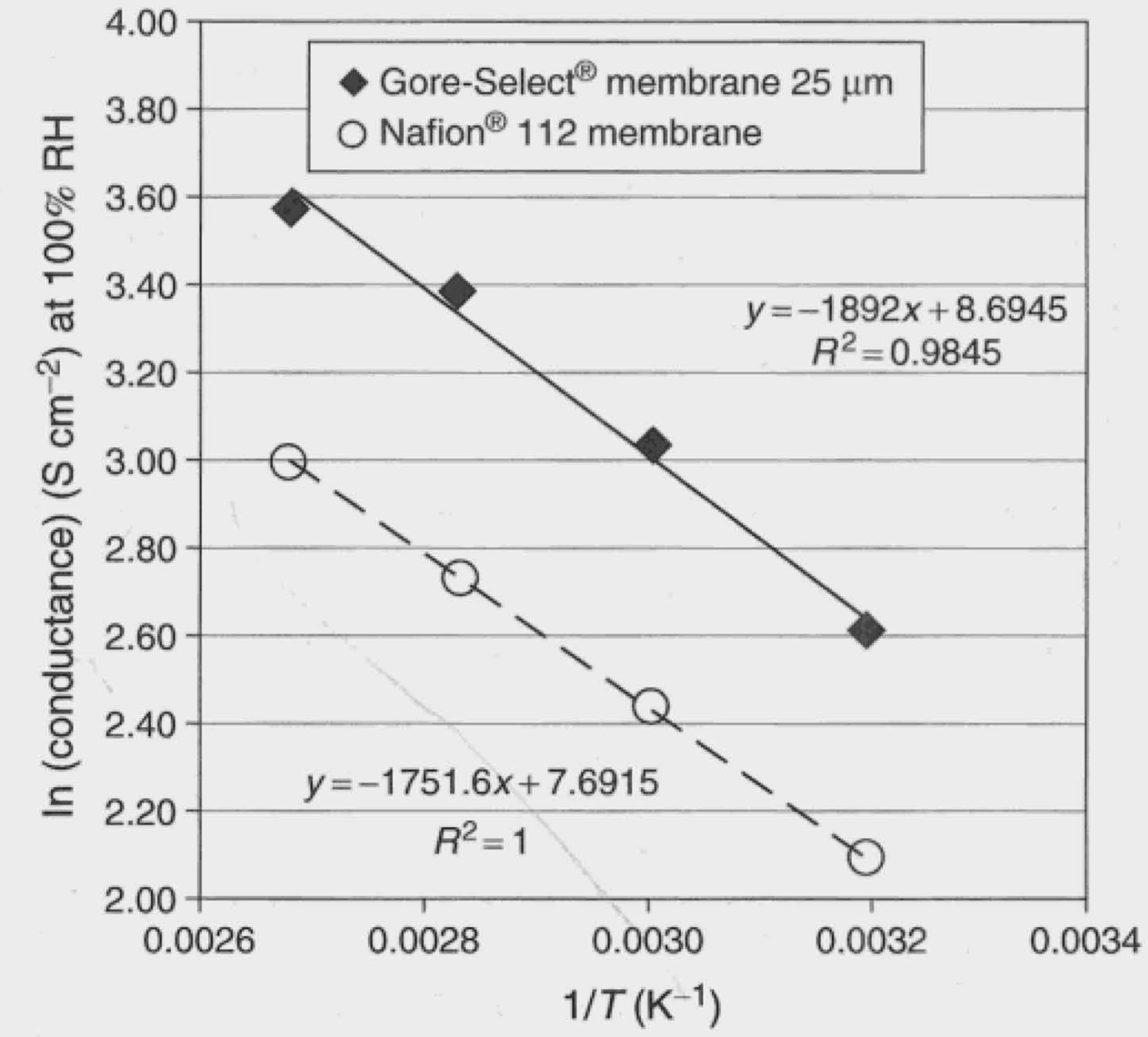

Figure 6. Arrhenius plot of conductance at 100% relative humidity as a function of temperature for a Gore-Select® membrane (25 μm) and Nafion® 112 membrane.

For both membrane types, membrane conductance demonstrates an Arrhenius correlation at 100% relative humidity for the temperature range 40–100 °C (Figure 6). Within this temperature range an activation energy (E_a) was calculated to be 15.7 and 14.6 kJ mol^{-1} for the 25 μm Gore-Select® membrane and Nafion® 112 membrane, respectively. (These values also demonstrate agreement with the literature.[13])

3 PERFORMANCE OF PRIMEA® MEAs, BASED ON THE GORE-SELECT® REINFORCED COMPOSITE MEMBRANE

The Primea® Series 55 MEA has been widely adopted in many fuel cell applications.[5–8] The single cell performance at a typical stationary fuel cell operating condition is demonstrated in Figure 7, with both hydrogen and simulated reformate fuels. Reformate performance of Primea® MEAs has been extensively reported elsewhere.[14, 15] The high power density achieved is a result of the combination of the high performance properties of the membrane and electrodes, and enables stationary fuel cell systems to operate at high power density at ambient pressure, where total systems efficiency can be maximized.

For many ambient pressure fuel cell applications, such as portable power and uninterruptible power supply (UPS)/back-up power, commercial acceptance requires development of high efficiency, high power density systems. An obvious method of systems simplification is to eliminate auxiliaries, such as air humidification and water recovery systems. Primea® Series 55 MEA, based on a 25 μm Gore-Select® membrane performance, is observed to demonstrate very little performance loss when cathode relative humidity is reduced from 100% to less than 20% (Figure 8). Compare this to the results obtained for the Nafion® 112 membrane based MEA (with the same electrodes), which exhibits lower performance with saturated reactant inlets, but also demonstrates a large loss in performance as the air relative humidity is reduced. These results directly demonstrate the benefit of the thin reinforced Gore-Select® membrane technology.

When the air inlet is fully saturated, the majority of the difference in Nafion® and Gore-Select® membrane performances can be accounted for by the differences in measured membrane resistance. Therefore, the ohmic drop (IR) compensated voltages for the two membrane families are very similar at the saturated condition (Figure 9). When the air inlet relative humidity is reduced, the IR compensated voltage for the Gore-Select® membrane shows little change,

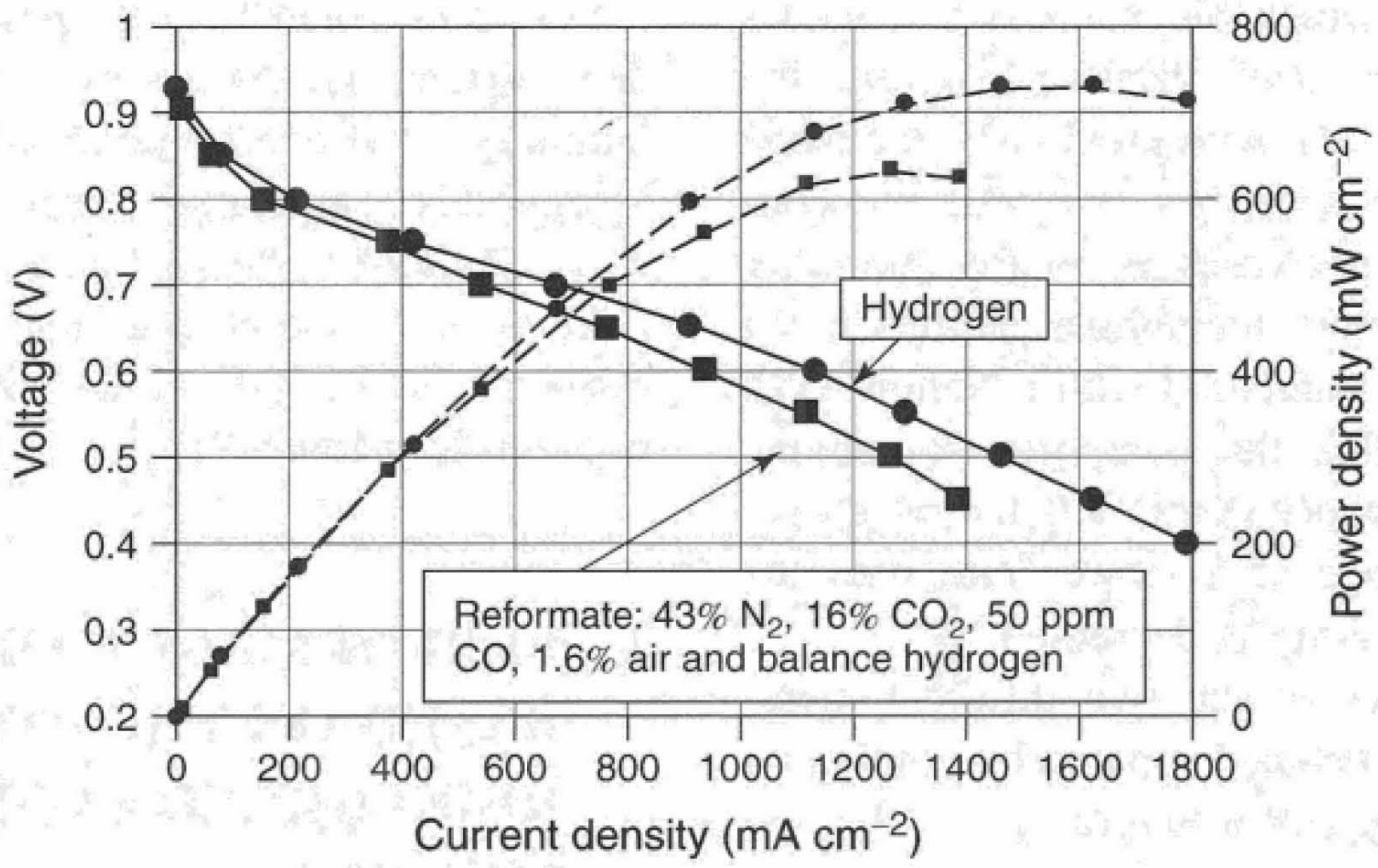

Figure 7. Polarization and power density curves for Primea® MEA Series 5561 based on 25 μm Gore-Select® membranes assembled with Carbel™ gas diffusion media CL. Cell temperature 70 °C. Ambient pressure air at 2.5 × stoichiometric flow at 100% RH. Ambient pressure fuel at 1.2 × stoichiometric flow of hydrogen at 100% RH.

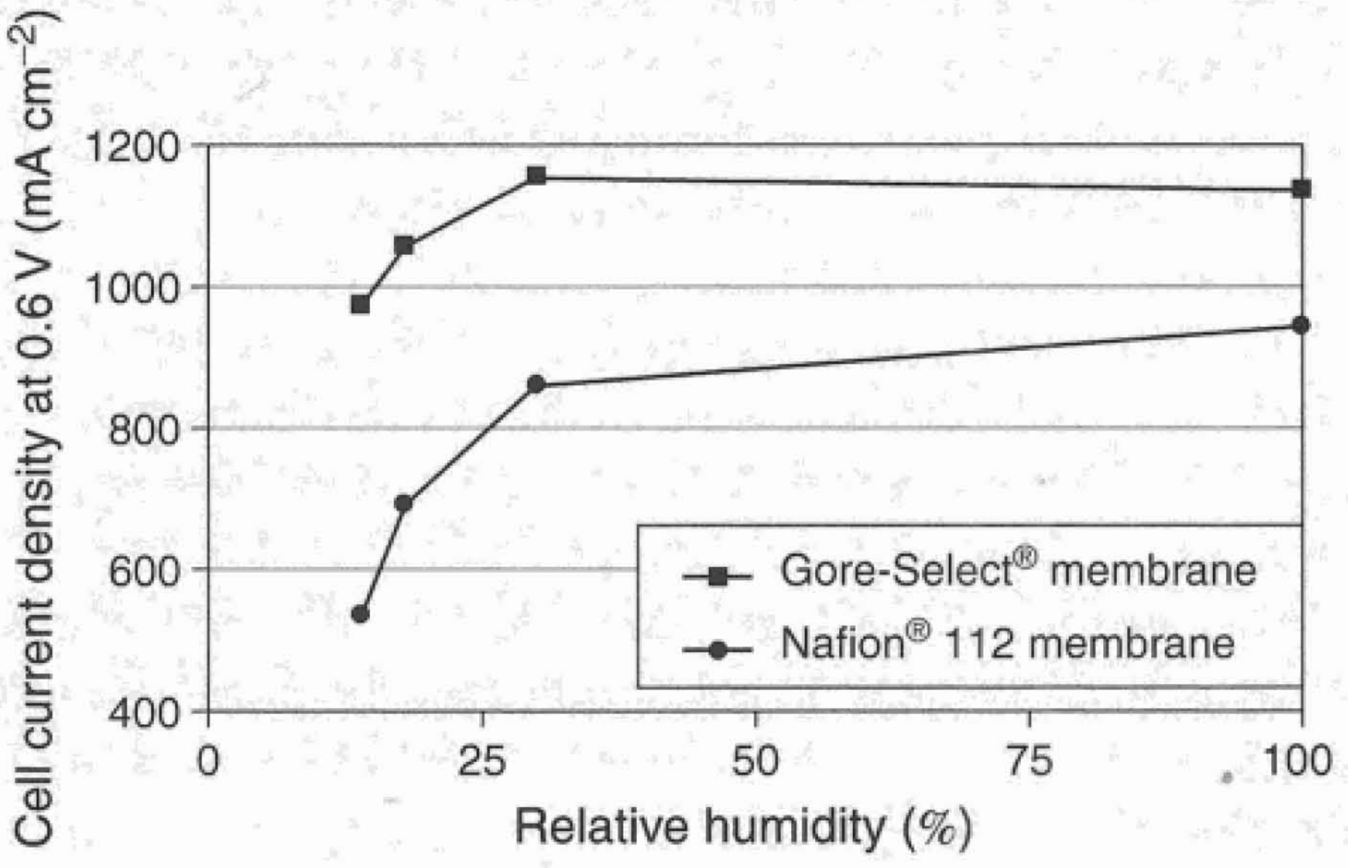

Figure 8. Comparison of Nafion® 112 and Gore-Select® membrane based fuel cell current density at 0.6 V as a function of cathode air inlet relative humidity. Cell temperature 70 °C, ambient pressure hydrogen and air, with anode inlet at 100% relative humidity.

while a significant decrease in the IR compensated voltage is observed in the case of the Nafion® 112 membrane. This effect is more significant at higher current density.

The effect gives rise to an additional benefit of thin low EW membranes beyond their increased conductance and the slower rate of conductance loss for Gore-Select® membrane as relative humidity is decreased (fitted exponents, *b*, in the equations in Figure 5). For the case of the thin membrane technology, rapid water transport (diffusion) is facilitated throughout the MEA. Therefore, membrane and MEA hydration remain uniform and no significant performance loss is observed at dry conditions. In this experiment, when the cathode relative humidity is reduced, the performance loss unaccounted for by IR compensation in the Nafion® 112 membrane is attributed to reduced cathode catalyst layer performance under dry conditions; water diffusion in Gore-Select® membranes is rapid enough to mitigate this performance loss.

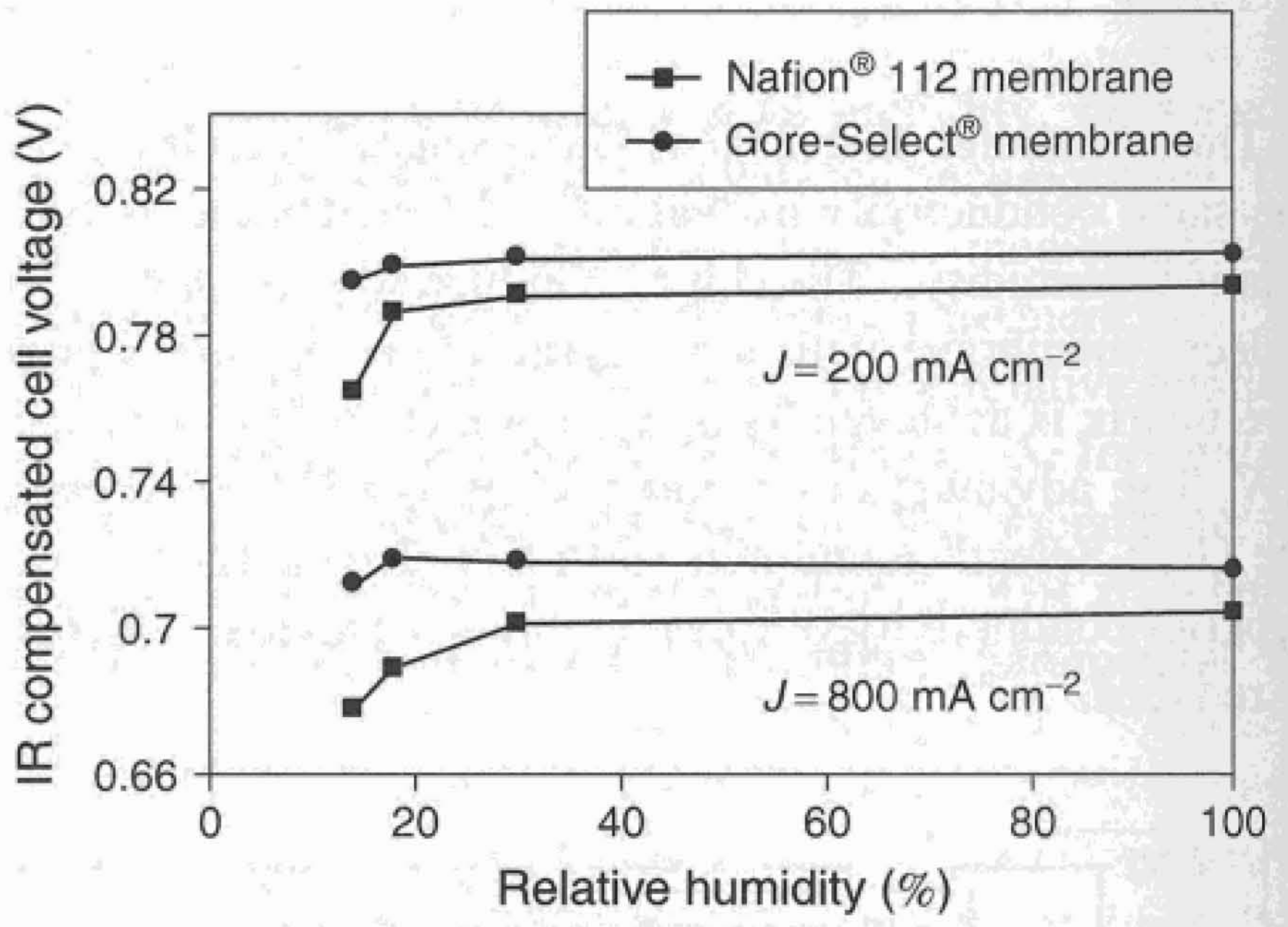

Figure 9. Comparison of Nafion® 112 and Gore-Select® membrane based fuel cell performance IR compensated voltage as a function of cathode air inlet relative humidity. Cell temperature 70 °C, ambient pressure hydrogen and air, with anode inlet at 100% relative humidity.

The importance of membrane hydration uniformity in achieving high fuel cell performance has been previously realized.[16] However, at Gore this advantage has also been demonstrated to play a key role in membrane durability (see next section).

The advantage of reducing polymer electrolyte membrane thickness has similarly been demonstrated by comparing MEA performance in full active area automotive stacks (Figure 10). When polarization data in a pressurized stack containing both Nafion® 112 and Gore-Select® membrane based MEAs operated with fully saturated reactants are

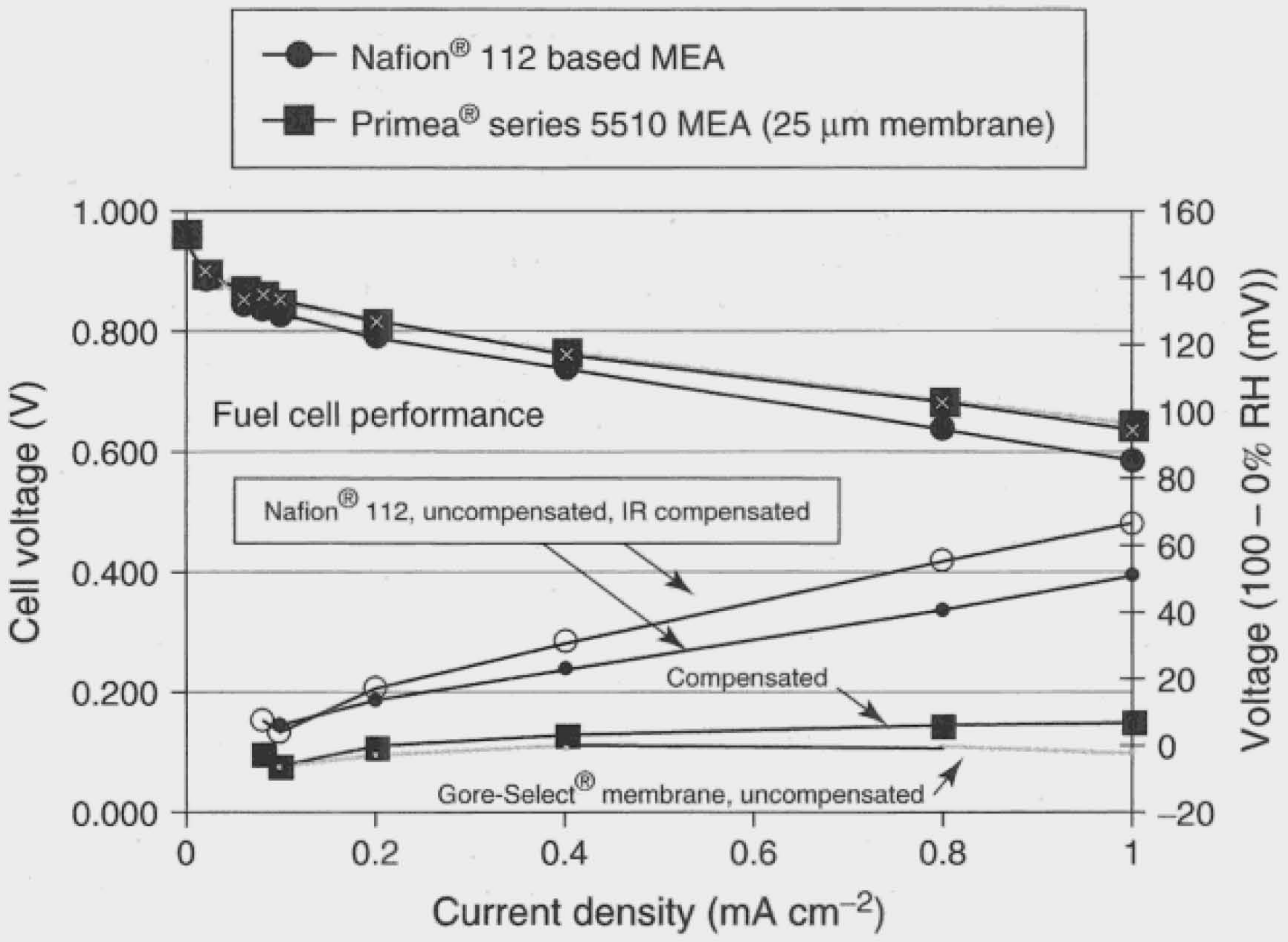

Figure 10. Comparison of Nafion® 112 and Gore-Select® membrane 25 μm based MEAs: Polarization performance and difference in polarization performance in cells operated with either dry or 100% RH cathode humidification (100% RH anode in both experiments). General Motors (GM) Global Alternative Propulsion Center (GAPC) 500 cm^2 fuel cell stack at cell temperature 80 °C, hydrogen and air reactants at 2.0× stoichiometric flow and 270 kPa operating pressure.

compared a greater than 50 mV performance difference is observed at 1 A cm^{-2}. However, from the perspective of automotive systems simplification, size, weight and efficiency it is extremely advantageous to operate automotive systems without external air humidification. A comparison of the IR compensated and non IR compensated voltage difference when operating the cell with dry and fully humidified reactant inlets is also reported (Figure 10). When operating Nafion® 112 membrane dry, a further loss in fuel cell performance is observed, which increases as a function of current density. Again, IR compensation does not fully account for the voltage differences observed between operating saturated and dry. The voltage loss incurred, which cannot be accounted for by IR compensation, is also observed to increase as a function of cell current density. The performance difference between dry and humidified conditions for cells operated with Gore-Select® membrane is small (10 mV at 1 A cm^{-2}), and this difference is eliminated when the voltage differences are IR compensated (For related issues refer to **Beginning-of-life MEA performance — Efficiency loss contributions**, Volume 3).

4 DURABILITY OF THE GORE-SELECT® MEMBRANE AND PRIMEA® SERIES MEAs

More recent product development work at Gore has focused on developing more durable products for commercial stationary fuel cell applications.[17–19] Initially, designed experiments were used to identify the key factors influencing membrane life and to determine the controlling MEA degradation mechanisms. This work led to development of experimental methods both in-cell and out-of-cell to accelerate key degradation mechanisms. The accelerated tests were used as tools to develop new, longer-life products.

Central to product development has been the understanding of factors influencing membrane life and the insight gained into fuel cell membrane degradation mechanisms. Gore's thin composite membranes have been found to have significant durability advantages over much thicker nonreinforced membranes. Results from accelerated membrane fuel cell tests (Figure 11) indicate very different failure characteristics when comparing reinforced and non-reinforced membranes. In this test, the MEA is operated under an accelerated test protocol, with periodic interruption to perform electrochemical analysis of hydrogen crossover. A membrane is reported to have failed when the hydrogen crossover current density exceeds approximately 15 mA cm^{-2} (this is an arbitrary value of hydrogen crossover used to provide a consistent criteria to end tests, even though at this hydrogen permeation rate, no loss in fuel cell performance is observed). Non-reinforced membranes (with thickness ranging from 25 to 90 μm) were all found to fail unpredictably and catastrophically in accelerated testing. It is very important to report that the Nafion® 112 membrane (the only 1100 EW membrane tested) based

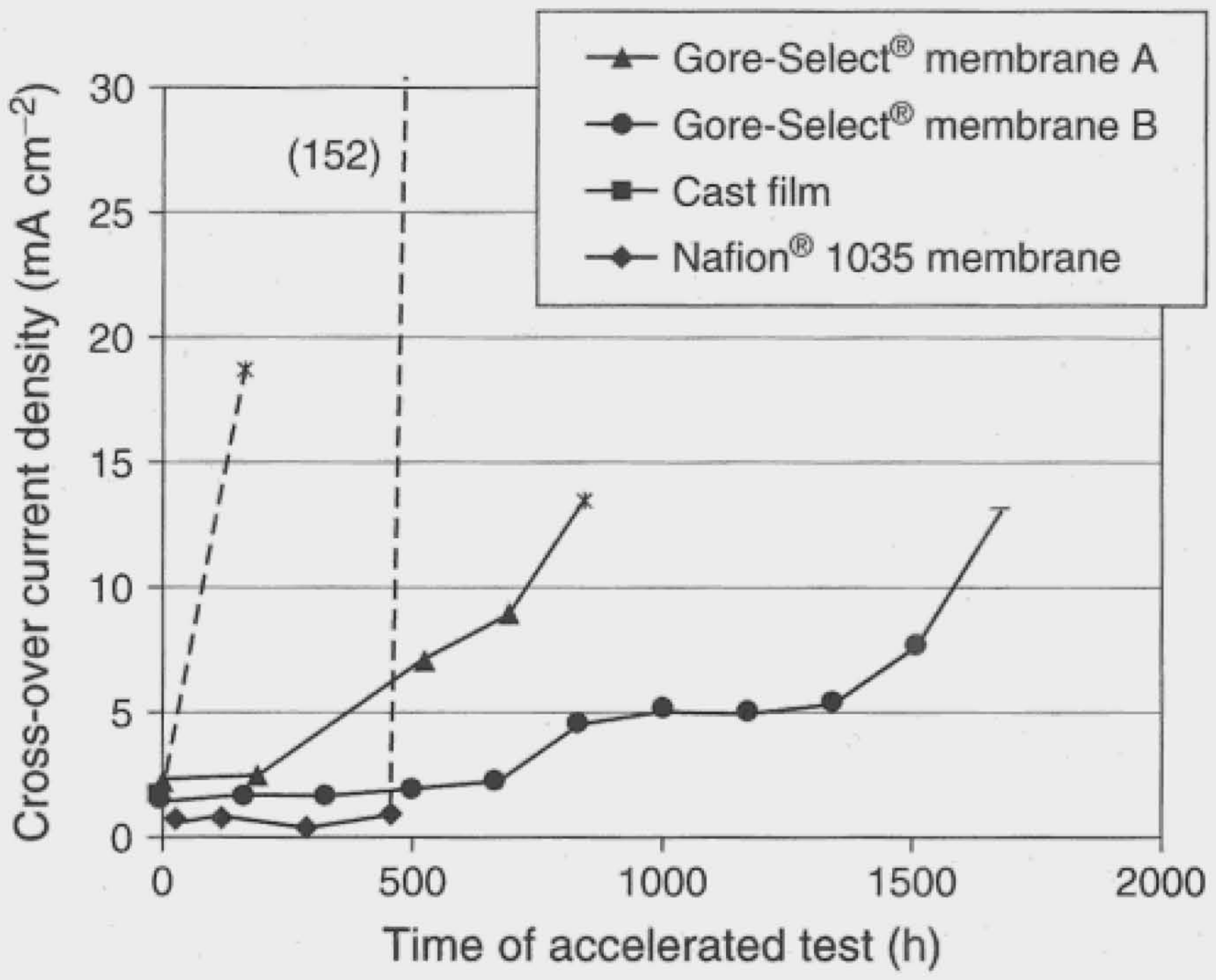

Figure 11. Hydrogen crossover current density as a function time for fuel cell (25 cm^2 active area) accelerated test of a series of MEAs based on reinforced and nonreinforced membranes (approximate thickness between 25 and 35 μm, with the exception of the 90 μm Nafion® 1035 membrane). Accelerated test conditions are: Constant current density 800 mA cm^{-2}. Cell temperature 90 °C, with hydrogen and air reactants at 75% RH and at 15 psig. (Reproduced from Liu *et al.* (2001)[19] with permission from Ecole Polytechnique de Montréal.)

MEA could not be operated at the specified conditions of the accelerated test. In order to perform an experiment with Nafion® 112 membrane both cell temperature (effectively increasing RH) and operating current density were reduced to allow the cell to run, therefore, time to failure of this membrane cannot be directly compared to others tested. It was concluded that membrane EW has a strong effect on its ability to operate at dry conditions. On completion of the test, the Nafion® membranes were typically observed to show a large tear or hole. Reinforced membranes (Gore-Select® membranes A and B) operated in the accelerated test were observed to offer superior life. For example, Gore-Select® membrane (A – 25 μm thick) failed at 800 h compared to the 500 h life of a 90 μm nonreinforced membrane (Nafion® 1035 membrane, 1000 EW). Reinforced membrane failures are characterized by a very small, gradual increase in hydrogen crossover current density as a function of time, which does not lead to a catastrophic loss in membrane integrity. This gradual increase in hydrogen crossover allows the life of reinforced membranes in this test to be predicted from monitoring the rate of increase in hydrogen crossover. The results (Figure 11) also demonstrate a new Gore-Select® membrane B, now incorporated in the new Primea® MEA Series 56 stationary MEA, which has close to twice the life of the standard membrane in this accelerated test (fails at 1700 h).

The lifetimes of reinforced Gore-Select® membranes in the accelerated tests were correlated to measured membrane lifetimes in fuel cells operated at realistic stationary conditions (Figure 12). The results show that Gore-Select® membrane A has a life of approximately 8000–9000 h at realistic conditions, while during accelerated testing this membrane fails at approximately 800–900 h. Therefore, it appears that from testing Gore-Select® membrane A, the accelerated test can be used as a predictive means of estimating membrane life by using an acceleration factor of 10×. Confirmational life testing is currently underway for the new longer life membrane developed for the Primea® Series 5621 MEA (Gore-Select® membrane B).

Authors[20] have previously reported that the fluoride ion release rate can be used to determine the rate of chemical degradation of ionomers and to predict membrane life in PEMFCs. At both accelerated and realistic operating conditions, fluoride release rate in the fuel cell product water was measured as a function of time, over a time-weighted average (Figure 13). At the realistic testing condition, the fluoride ion release rate varies from 1×10^{-8} to 10×10^{-8} g (F$^-$) cm^{-2} h^{-1}, while at the accelerated test condition, the fluoride ion release rate varies from 1×10^{-7} to 6×10^{-7} g (F$^-$) cm^{-2} h^{-1}. Therefore, as a first approximation, the rate of fluoride ion release, and therefore, the rate of chemical degradation of the ionomer increased as a result of the harsh operating conditions of the accelerated fuel cell test. However, within a test condition, the measured fluoride ion release rate can vary up to an order of magnitude within replicate tests, even though these replicate tests demonstrate a very reproducible membrane life. Also, within a single membrane life test at either accelerated or realistic conditions, a wide range in membrane

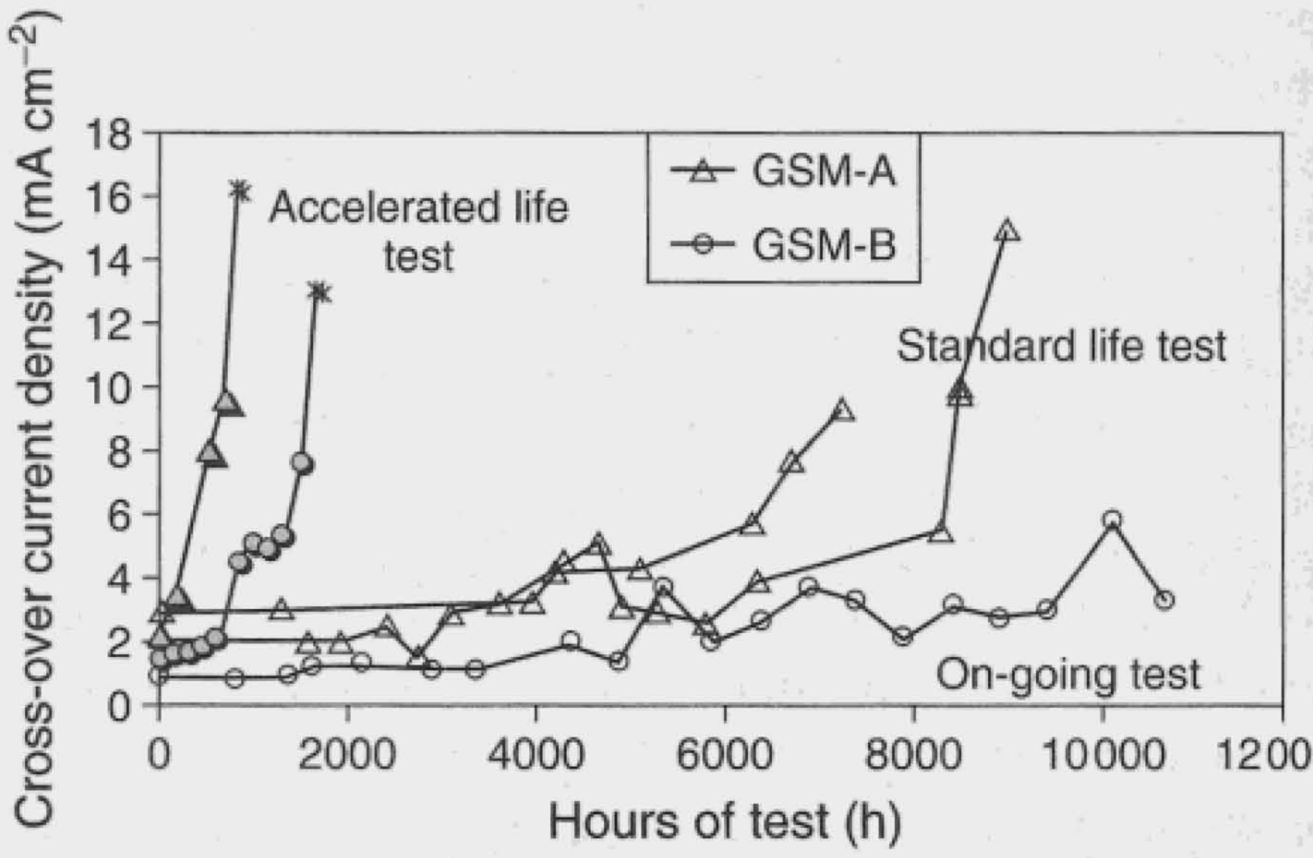

Figure 12. Hydrogen crossover current density as a function of time in fuel cell tests (25 cm^2 active area), comparing results at realistic conditions (cell temperature 70 °C, fully saturated hydrogen and air at ambient pressure) and accelerated conditions (see Figure 11 for conditions).

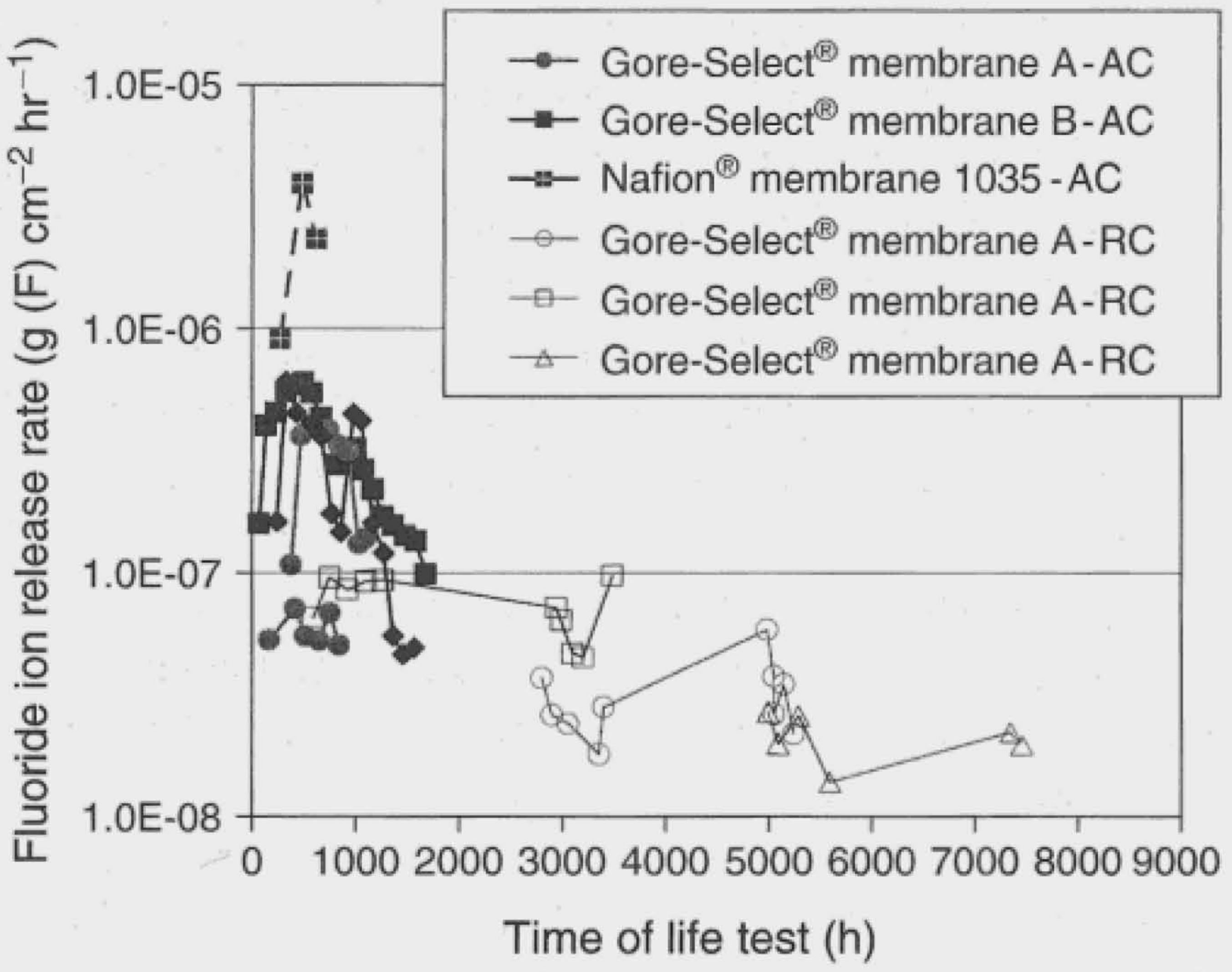

Figure 13. Fluoride ion release rates as a function of time in fuel cell tests (25 cm^2 active area) operated at realistic and accelerated test conditions (AC, accelerated test condition; RC, realistic test condition).

fluoride ion release rates were measured as a function of time.

The total percentage ionomer loss from a membrane has also been considered as a method of predicting membrane life at accelerated conditions. However, similar problems have been encountered, in that tests with the same membrane have shown poor reproducibility and there is no correlation between membrane life and total percentage ionomer loss.[19] In conclusion from our work to date, membrane life cannot easily be correlated to fluoride ion release rate or total ionomer loss, and thus implying that membrane life is not governed by the rate of chemical degradation of the membrane.

The different nature of the membrane failures observed for reinforced and nonreinforced membranes, the superior lifetimes of reinforced-composite membranes, along with the unpredictable results of the fluoride ion release rate data, suggest that the membrane failure mechanism in our tests is strongly influenced by the mechanical properties of membranes. It is proposed that membrane failures occur as a result of physical defect formation and propagation to failure. Physical defects may form in an MEA during cell assembly or as a result of ionomer degradation during operation, either within the membrane or on the membrane surface. In the case of nonreinforced membranes, crack propagation from the defect will rapidly lead to catastrophic membrane failure. The presence of the ePTFE reinforcement used in the composite Gore-Select® membrane structure may hinder or slow down this crack propagation and hence, significantly increase the life of the PEMFC membrane. Therefore, the life of a perfluorosulfonic acid PEMFC membrane is strongly affected by the mechanical properties of the membrane.

Although this chapter has only considered fuel cell durability from the perspective of membrane durability, a similar product development methodology has been applied to all components of the MEA, resulting in development of the Primea® Series 56 MEA, designed for commercial stationary systems.[17, 18]

5 COMMERCIAL ASPECTS

One of the largest barriers to the wide adoption of fuel cells has always been cost. The MEA is a central component of the fuel cell system, and strongly influences the cost, size, weight, and complexity of the overall system. There are three ways in which Gore's Primea® MEA technologies may inherently contribute to lowering system cost to the levels required for commercialization. The first is directly related to the reduced material content of thin membranes. Utilizing thin Gore-Select® membranes, a unique combination of long life and high power density is possible, as has been highlighted earlier in this chapter. However, an additional benefit associated with these thin membranes is reduced ionomer content. As an example, a 20 μm Gore-Select® composite membrane contains about one third the ionomer content per square meter as the thinnest commercially available nonreinforced membrane (Nafion® 112 membrane). Ionomer is one of the most costly materials in a fuel cell stack, so minimizing the amount of materials is a critical factor in reducing stack cost.

The second area of cost savings made possible by Primea® MEAs is in the area of total stack cost, as a result of higher power density. Gore's low resistance membranes offer considerable power density advantages over competitive membranes. The result is that the fuel cell stack becomes smaller and lighter, which is critical for some applications; furthermore fewer MEAs are needed to produce the same amount of power, therefore material content in the stack is reduced. This is valuable as it not only reduces MEA material requirements (catalyst and ionomer), but also means less bipolar plate material and fewer gas diffusion media are needed.

The final area where cost savings can be realized through Primea® MEA technology is in total system cost as a result of system simplification. A considerable portion of the complexity and cost of a fuel cell system is associated in auxiliary stack conditioning components, which create an optimum operating environment within the stack. Examples are; keeping the gas streams well

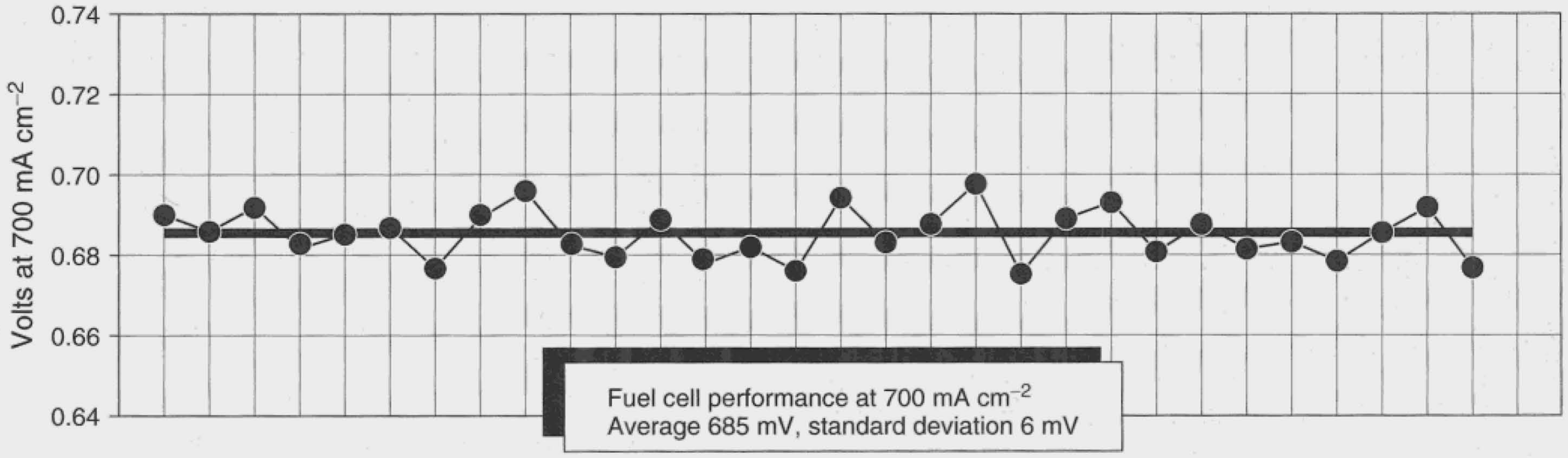

Figure 14. Primea® MEA Series 5510 fuel cell performance control chart for a recent 6 month production period. Fuel cell voltage at 700 mA cm^{-2} is reported in an ambient pressure quality assurance test. (The conditions of the test are described in the legend to Figure 7 for hydrogen fuel).

humidified, maintaining a low stack temperature, recovering water from the gas stream outlet, and removing trace amounts of impurities such as CO, which all add cost to a fuel cell system. If the stack can operate under more severe conditions, then many of these auxiliary stack components can be downsized or eliminated. Primea® MEAs can operate very well with reduced humidification, which allows humidification systems to be reduced or eliminated, and can even eliminate the need for water recovery technologies at the outlet stream. Because of the reduced tendency to dry out, operating at higher temperatures is possible with Gore's MEAs, which both increases CO tolerance and reduces the cooling section requirements of a system. As a result, the system around a stack with Gore MEAs can be a simpler and lower cost system.

These three additive benefits; reduced membrane cost through reduced material content, reduced stack cost through higher power density, and reduced system cost through system simplification, all contribute to significant cost savings in a fuel cell system. Gore has been producing high quality MEAs in production volumes for over five years, and has developed very efficient, high volume production techniques. Although the industry is just developing today, high quality standards must be met, and even higher standards will be required in the future. Gore is continuously monitoring and improving the quality of its products, and has been able to meet the needs of the emerging PEMFC industry. Below is an example of the type of batch-to-batch variability Gore measures on its products produced and provided to the industry over the last six months. At least one MEA from each production run is tested in a fuel cell to measure its output in a standard ambient pressure fuel cell test protocol developed at Gore. The lot to lot variability is very small with a standard deviation of 6 mV, with an average performance of 0.685 mV at 700 mA cm^{-2} (Figure 14).

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