A Study of Na\textsubscript{x}Pt\textsubscript{3}O\textsubscript{4} as an O\textsubscript{2} Electrode Bifunctional Electrocatalyst

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December 1991
A STUDY OF NaₓPt₃O₄ AS AN O₂ ELECTRODE

BIFUNCTIONAL ELECTROCATALYST

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SUMMARY

The present study suggests that PTFE-bonded NaₓPt₃O₄ gas porous diffusion electrodes may be a viable candidate for bifunctional O₂ reduction and evolution activity. The electrodes exhibited Tafel slopes of about 0.06 V/decade for both O₂ reduction and evolution. For O₂ reduction, the 0.06 slope doubled to 0.12 V/decade at larger current densities. Preliminary stability testing at 24 °C suggested that the NaₓPt₃O₄ electrodes were relatively stable at reducing and oxidizing potentials typically encountered at the O₂ electrode in a regenerative fuel cell.

INTRODUCTION

Efficient, long-life energy storage systems will be required for many future NASA missions such as LEO or GEO space platforms and lunar or martian bases. One candidate for these missions is the alkaline regenerative H₂-O₂ fuel cell in conjunction with a photovoltaic array. For example, the dedicated two-unit H₂-O₂ system consists of a fuel cell which uses H₂ and O₂ to produce power during the dark portion and of an electrolyzer which uses power to regenerate the H₂ and O₂ during the light portion.

Some of the more desirable characteristics for H₂-O₂ fuel cell systems, particularly for long-time automated operation, are high energy density, small volume, high efficiency, high reliability and long life. A recent GEO mission analysis indicated that a significant increase in energy density is possible if a two-unit alkaline fuel cell and electrolyzer system is replaced with a single-unit alkaline fuel cell/electrolyzer system (ref. 1).

The efficiencies of fuel cell and electrolyzer systems under load are considerably less than 100 percent due, primarily, to the irreversibility of the O₂ electrode. Therefore, active bifunctional O₂ electrocatalysts are needed to increase the kinetics for both O₂ reduction and evolution to maximize the efficiency of a single-unit alkaline fuel cell/electrolyzer system.

Metals and oxides have been investigated as candidates for monofunctional O₂ electrocatalysts for alkaline fuel cells and electrolyzers. For example, a Au-10 percent Pt electrocatalyst, developed by International Fuel Cells Corporation (IFC), is being used as a cathode for O₂ reduction in the space shuttle's alkaline H₂-O₂ fuel cell (refs. 2 and 3). Similarly, NiCo₂O₄ may be an attractive electrocatalyst candidate for O₂ evolution in an alkaline electrolysis cell (refs. 4 and 5). Studies of bifunctional O₂ electrocatalysts, however, are rare or unpublished.

In addition to showing acceptable bifunctional O₂ activity, a long-life candidate must also be stable under both reducing and oxidizing conditions. Although Pt and Pt alloys exhibit moderate bifunctional O₂ electrode activity, long-time stability for Pt, particularly during O₂ evolution, is questionable. Pt bronzes, composed of oxides of Pt and an alkali metal, are
believed to have greater stability than metallic Pt particularly under oxidizing potentials. Na-Pt bronze powders (i.e., Na$_x$Pt$_{3}$O$_4$) have been prepared by Giner, Inc. as single phase and in moderately high surface area. Giner, Inc. fabricated PTFE-bonded gas porous diffusion electrodes for the present study using mixtures of Na$_x$Pt$_{3}$O$_4$ powders as the electrocatalyst and polytetrafluoroethylene (PTFE) as the binder.

The objective of the present study is to ascertain the usefulness of Na$_x$Pt$_{3}$O$_4$ as a bifunctional O$_2$ electrocatalyst for the O$_2$ electrode under alkaline conditions. Therefore, O$_2$ reduction and evolution activities and the stabilities of these PTFE-bonded electrodes were determined under both reducing and oxidizing conditions.

**EXPERIMENTAL**

**Na$_x$Pt$_{3}$O$_4$ Preparation and Electrode Fabrication**

Giner, Inc. prepared two similar batches (A and B) of single phase Na$_x$Pt$_{3}$O$_4$ powder by heating pellets of Na$_2$CO$_3$ and PtO$_2$H$_2$O to about 650 °C under an atmosphere of O$_2$ (refs. 6 and 7). The Na content in the Na$_x$Pt$_{3}$O$_4$ powder was estimated from the lattice constant $a_0$ obtained by x-ray diffraction. The relationship is as follows:

\[ a_0 = 0.11X + 5.585 \]  

(1)

where $X$ represents the Na content (ref. 8). Lattice constants of 5.673 and 5.668 Å were obtained for batches A and B, respectively. Therefore, compositions of about Na$_{0.80}$Pt$_{3}$O$_4$ and Na$_{0.75}$Pt$_{3}$O$_4$ were calculated for the two batches from equation 1. X-ray diffraction analysis showed no free Pt in either batch. The BET surface area was about 17 m$^2$/g for both batches. The conductivity of a compacted pellet of this Na$_x$Pt$_{3}$O$_4$ powder, determined by a 2-probe resistance measurement, was about 50 Ω-cm$^{-1}$.

Giner, Inc. fabricated 4 PTFE-bonded gas porous diffusion electrodes using batch A powder for electrodes 1 and 2 and batch B powder for electrodes 3 and 4. The PTFE contents for these 4 electrodes ranged between 20 and 35 percent of the Na$_x$Pt$_{3}$O$_4$. For each electrode, the catalyst-PTFE mixture was pressed with a Au plated Ni screen current collector and a Gortex$^1$ porous PTFE backing to form a "green" electrode. The Gortex backing serves as a barrier to the KOH electrolyte at the gas side but not to gaseous O$_2$. The resulting "green" electrodes was then heated at about 350 °C, by means of a proprietary procedure, to form the PTFE-bonded gas porous diffusion electrode. The loadings and PTFE contents for electrodes 1, 2, 3 and 4 are listed in table I.

O$_2$ reduction measurements for electrodes 1, 2, 3 and 4 indicated that O$_2$ transport became rate-controlling at relatively small current densities. Therefore, Giner, Inc. fabricated electrode 5 with a more balanced hydrophobic and hydrophilic catalyst-PTFE mix using Na$_{0.75}$Pt$_{3}$O$_4$ powder (batch B) in an attempt to increase the O$_2$ transport during O$_2$ reduction. The loading and PTFE content for electrode 5 are also listed in table I.

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$^1$Gortex is a trade name of W.L. Gore & Co.
Electrochemical Apparatus and Measurements

A floating electrode half-cell apparatus was used for all electrochemical measurements (ref. 9). A schematic of the floating half-cell is shown in figure 1. The PTFE-bonded electrode served as the working electrode with Au wire serving as the counter electrode. The reference electrode was a Hg/HgO electrode with a potential of 0.926 V versus a reversible H₂ electrode (RHE) in the same solution at 25 °C.² The temperature coefficient for this reference electrode is about \( -0.45 \text{ mV/°C} \) as determined by comparison with a dynamic H₂ electrode at various temperatures (fig. 2). An atmosphere of gaseous O₂ (N₂) was passed through a presaturator to minimize H₂O₂ loss in the half-cell.

Current-potential data were obtained galvanostatically by means of manual or computer driven systems. Both methods gave essentially the same values. For the computer driven system, the potentiostat (EG&G Princeton Applied Research Model 173) was interfaced with an Apple IIe computer by means of a EG&G Model 276 plug-in unit. A computer program (EG&G Electrochemistry Program Volume I) was used to drive and control the potentiostat.

iR polarizations were determined by means of an Electrosynthesis Corp. Model 800 IR instrument in conjunction with a 7 V Zener diode. The instrument interrupts the circuit periodically for a few microseconds. The diode limits the voltage rise to 7 V during the interruption. iR polarization values for correcting observed potentials were obtained from a plot of iR against current as illustrated in figure 3 for a typical run.

Experimental Procedure

The working electrode was introduced into the floating electrode half-cell to obtain the current-potential data with the electrocatalyst side of the electrode contacting the surface of the 30 percent KOH electrolyte. The electrode was then raised slightly to form a small meniscus at the electrode/electrolyte interface. Exact positioning of the electrode was not critical for determining the iR corrected potentials for small meniscus heights. For example, while an observed potential and iR may vary slightly with electrode positioning, the corresponding iR corrected potential remained essentially constant for a fixed current.

PTFE-bonded electrodes, operating as cathodes in an alkaline electrolyte, generally benefit from cathodic preconditioning to minimize initial polarization. Therefore, each electrode was preconditioned by slowly increasing the cathodic current to greater than -0.8 A while maintaining the potential above 0.3 V. This preconditioning process may require up to 0.5 hr.

Steady-state current-potential data were then obtained galvanostatically starting at the larger cathodic or anodic currents. At larger anodic currents, the potentials (and iR values) became erratic as illustrated in figure 4. Rapid O₂ evolution may force some of the KOH electrolyte out of the smaller pores (ref. 10). In addition, detachment of the O₂ bubbles, formed at the electrode/electrolyte interface, may become increasingly more difficult, particularly if these bubbles become trapped inside the tube holding the electrode. Therefore, O₂ evolution data were not recorded for anodic currents larger than 0.2 to 0.4 A/cm². For moderate currents, a steady-state condition was usually obtained after a relatively short time. Smaller currents may

²All potential values in this report will refer to RHE unless otherwise stated.
require slightly longer times. As an illustration, a steady-state condition was obtained after about 10 sec for an anodic run at 0.05 A/cm² while about 180 sec were required at 0.001 A/cm².

Preliminary runs had indicated that a working electrode may undergo a small irreversible change during cathodic aging even though it had been preconditioned previously. This is illustrated in figure 5 where the potential for the preconditioned electrode 5 increased slowly during the first 30 min. After this initial aging period, the potential remained essentially constant with time. Therefore, all electrodes were aged cathodically at about -0.01 A/cm² (or anodically at about 0.01 A/cm²) for about 4 hr prior to obtaining the respective O₂ reduction or evolution data. Current-potential data were then obtained galvanostatically.

The stabilities of electrode 5 at 24 °C were followed, both in the presence of O₂ and under an inert atmosphere of N₂, for longer periods.

For stability determinations under an inert atmosphere, electrode 5 was introduced into the half-cell under flowing N₂ and submerged below the surface of the KOH. For the first series of tests, corrosion currents were obtained. A cyclic voltammogram at 1 mV/sec over a large potential range gave very broad oxidation-reduction peaks at about 0.9 and 0.7 V as shown in figure 6. Therefore, a potential of 0.6 V was chosen for the corrosion measurements. The electrode was held potentiostatically at 0.6 V for 7 hr and the resulting cathodic currents were recorded periodically. For the second series of tests under N₂, electrode capacitances at about 0.45 V were calculated for a submerged electrode. The cyclic voltammogram in figure 6 had indicated that oxidation-reduction reactions are minimal between about 0.4 and 0.5 V. An initial cyclic voltammogram was obtained between 0.4 and 0.5 V at 1 mV/sec (fig. 7(a)). After this initial cyclic sweep, the electrode was then held at 0.6 V for a total of about 305 hr. The run was interrupted periodically and the cyclic sweeps were repeated to redetermine the electrode capacitances. The cyclic voltammogram at the end of the 305 hr is shown in figure 7(b).

For stability determinations in the presence of O₂, electrode 5 was placed in the floating half-cell in a manner similar to that used to obtain the current-potential data. For the first series of tests, the electrode was held anodically at 0.01 A for 121 hr. At the end of this period, the current was reversed and the sample was held cathodically at -0.01 A for 100 hr and then at -0.1 A for an additional 60 hr. For the second series of tests under O₂, another sample of electrode 5 was cycled at alternate periods of about 24 hr at anodic and cathodic currents of 0.01 and -0.01 A/cm². The potentials were recorded periodically during the 340 hr run. For a third series of tests, another sample of electrode 5 was cycled continuously under both reducing and oxidizing conditions. Initially, the electrode was held at 0.827 V for 60 sec and the initial cathodic current was recorded. Then, the electrode was swept continuously at 1 mV/sec between 0.827 and 1.446 V. The cycling was interrupted periodically and the cathodic currents were redetermined at 0.827 V. This procedure was repeated for a total of 1132 cycles (390 hr).

RESULTS AND DISCUSSION

O₂ Reduction

The Na content in electrode 1 and 2 differed somewhat from that in electrodes 3 and 4 with compositions of about Na₀.₈₀Pt₃O₄ and Na₀.₇₂Pt₃O₄, respectively. It is assumed, however,
that this small change in Na composition is not a major factor in controlling the kinetics of \( \text{O}_2 \) reduction.

Current-potential \( \text{O}_2 \) reduction data were obtained for aged electrodes 1, 2, 3 and 4 at 80 °C. Polarization potentials were calculated by subtracting the iR corrected potentials from the corresponding thermodynamic potential (i.e., 1.181 V at 80 °C). Tafel plots were obtained by plotting these polarization potentials against the logarithms of the geometric current densities. The Tafel data for each of these 4 electrodes could be fitted to two straight line regions. This is illustrated in figure 8 for electrode 3 where the \( \text{O}_2 \) reduction data at 80 °C were fitted to 2 regions with slopes of about 0.06 and 0.12 V/decade. The corresponding intercepts for these 4 electrodes are listed in table II.

The \( \text{Na}_x\text{Pt}_3\text{O}_4 \) loading levels for electrodes 1, 2, 3 and 4 varied between 13.6 and 24.5 mg/cm\(^2\) of geometric area (table I). It seems reasonable to assume that the kinetics for \( \text{O}_2 \) reduction can be normalized to the \( \text{Na}_x\text{Pt}_3\text{O}_4 \) loading levels if the electrode structures are similar. Therefore, the geometric exchange current densities for \( \text{O}_2 \) reduction for these 4 electrodes were normalized to 20 mg/cm\(^2\) of \( \text{Na}_x\text{Pt}_3\text{O}_4 \) at 80 °C. These values are also listed in table II. \( \text{O}_2 \) reduction Tafel data were calculated for the 4 electrodes using the normalized geometric exchange current densities and the slopes. The resulting plots are shown in figure 9.

One model for PTFE-bonded gas porous diffusion electrodes assumes that catalyst particles form porous electrode agglomerates which are flooded with electrolyte and that the PTFE creates hydrophobic gas channels. When current is drawn from the electrode, the gas diffuses through the hydrophobic channels, dissolves in the electrolyte in the agglomerate and then reacts at the catalyst surface sites (ref. 11). A mathematical model for this type of electrode suggested that at smaller or moderate current densities, where the catalyst is utilized more effectively, the reaction process is activation controlled with a Tafel slope value that is essentially equal to that of a smooth electrode. However, at larger current densities, where the catalyst is not so well utilized, the reaction process changes from activation control to diffusion control with a corresponding Tafel slope of about double that for a smooth electrode (ref. 12).

The Tafel slope for \( \text{O}_2 \) reduction at electrodes 1, 2, 3 and 4 increased from 0.06 to 0.12 V/decade. Similar to that suggested in reference 12, this doubling of the slope is believed to be indicative of a change from activation control for the 0.06 region to diffusion control for the 0.12 region. As seen in figure 9, this change to diffusion control occurred at relatively small current densities. This suggests that electrodes 1, 2, 3 and 4 were too hydrophobic leading to insufficient KOH access. Improved \( \text{O}_2 \) reduction performance may require a better balance between the hydrophobic and hydrophilic electrode character.

Even though all 4 electrodes were assumed to be excessively hydrophobic, figure 9 suggests that the PTFE content is still an important factor to be considered for improving the \( \text{O}_2 \) reduction performance at \( \text{Na}_x\text{Pt}_3\text{O}_4 \) electrodes. This is illustrated by the \( \text{O}_2 \) reduction activity for the 4 electrodes which increased with increasing PTFE content. For example, the polarizations for electrodes 3 and 4, containing 30 and 35 percent PTFE, were considerably smaller than that obtained for electrode 1 (20 percent PTFE).

As will be discussed later, the reverse effect was observed for \( \text{O}_2 \) evolution. Smaller PTFE contents of 20 to 25 percent may lead to increased \( \text{O}_2 \) evolution activity. Optimization of a \( \text{Na}_x\text{Pt}_3\text{O}_4 \) electrode for maximum bifunctional \( \text{O}_2 \) reduction and evolution activity may require an intermediate PTFE content in addition to a more balanced hydrophobic/hydrophilic
character. Therefore, Giner, Inc. fabricated electrode 5 with a PTFE content of 25 percent and a better balance in its wettability in an attempt to utilize a larger portion of the electrode interior and to increase the O$_2$ transport to this surface.

O$_2$ reduction data were then obtained for aged electrode 5 at temperatures ranging between 24 and 93 °C. The corresponding intercepts and geometric exchange current densities for electrode 5 are listed in Table III. While only 2 regions were observed for electrodes 1, 2, 3 and 4 for the current density ranges used, data for electrode 5 could be fitted to 3 straight line regions for each temperature. This is illustrated in figure 10 where the data at 24 °C were fitted to lines with slopes of 0.04, 0.06, and 0.12 V/decade. Presumably, the 0.04 region would have been obtained for electrodes 1, 2, 3 and 4 if sufficiently small current densities had been used. Similar to the assumption made for electrodes 1, 2, 3 and 4, the observed doubling of the Tafel slope from 0.06 to 0.12 V/decade for electrode 5 suggests that diffusion is controlling for the 0.12 region.

The data for electrode 3 is also shown in figure 10 as a dashed line for comparison. This comparison indicates that utilization of the electrocatalyst in electrode 5 was greatly increased by the improved electrode structure and an increased wettability of this electrode. For example, the geometric exchange current density for electrode 5 at 80 °C for the 0.06 V/decade region is about 4.5x10$^{-7}$ A/cm$^2$. The corresponding normalized geometric exchange current density for electrode 2 was about 2 orders of magnitude smaller. In addition, diffusion becomes rate controlling for electrode 5 at 80 °C at about 0.2 A/cm$^2$. The corresponding value for electrode 4 was a much smaller value (i.e., 0.004 A/cm$^2$).

The O$_2$ reduction data for electrode 5 for the various temperatures are shown in figure 11. The polarizations for O$_2$ reduction decreased with increasing temperatures indicative of an activation process.

The "apparent" energy of activation, $E_A^*$, for O$_2$ reduction at electrode 5 was calculated as follows:

$$E_A^* = -(2.3R) \left[ \frac{d \log i_o}{d(1/T)} \right]$$

(2)

where $R$ is the gas constant and $i_o$ is the exchange current density (ref. 13). A value of about 5.6 kcal/mol was calculated for the "apparent" energy of activation for O$_2$ reduction at electrode 5 for the 0.06 V/decade region (fig. 12(a)). An even smaller value of about 3.4 kcal/mol was calculated for the 0.12 region (fig. 12(b)). This smaller value for the 0.12 region (<5 kcal/mol) may be indicative of a largely diffusion controlled process (ref. 14 and 15). This is in agreement with the previous assumption that the doubling of the slope from 0.06 to 0.12 V/decade indicated a change from activation to diffusion control.

O$_2$ reduction data for electrode 5 at 80 °C are compared in figure 13 with data reported for a similar type of PTFE-bonded Na$_x$Pt$_3$O$_4$ electrode at 80 °C (ref. 6) and with data reported for an IFC Orbiter Au-10 percent Pt fuel cell electrode (ref. 3). Giner, Inc. reported data for an electrode which used a loading of about 20 mg/cm$^2$ Na$_{0.8}$Pt$_3$O$_4$ powder (20 m$^2$/g) and a PTFE content of about 25 percent PTFE (ref. 6). Polarization values were estimated from the data
taken from the figure in reference 6 and these values are shown in figure 13 as triangles. The O₂ reduction polarization for the electrode reported in reference 6 was somewhat smaller than that which was obtained for electrode 5. This difference in polarization, however, was not large and may have been due to a more complete optimization of the reference 6 electrode. Data was reported for an IFC Orbiter fuel cell electrode (ref. 3). This electrode contained Au-10 percent Pt powder (10-15 m²/g) as the electrocatalyst. These data are presented in figure 13 as a dotted line with slopes of about 0.04 and 0.12 V/decade. The polarization for the IFC electrode was somewhat smaller than that of electrode 5 and was essentially equal to that estimated from the figure in reference 6.

O₂ Evolution

Current-potential O₂ evolution data were obtained for aged electrodes 1, 2, 3 and 4 at 80 °C. The iR corrected Tafel data for electrodes 1, 3 and 4 could be fitted to 2 straight line regions. This is illustrated in figure 14 where the O₂ evolution data for electrode 1 were fitted to 2 regions with slopes of 0.06 and 0.12 V/decade. However, the data for electrode 2 could be fitted to three regions as shown in figure 15. In addition to the 0.06 and 0.12 regions, the data for electrode 2 were fitted to a line with a slope of 0.04 V/decade at the smaller current densities. Presumably, the 0.04 region would have also been observed for electrodes 1, 3 and 4 if sufficiently small current densities had been used. The corresponding intercepts for these 4 electrodes are listed in Table IV. The geometric exchange current densities for these 4 electrodes at 80 °C were normalized to 20 mg/cm² and these values are also listed in table IV. O₂ evolution Tafel data were calculated for these electrodes and the results are shown in figure 16.

Similar to that assumed for O₂ reduction, the doubling of the slope for the 0.06 and 0.12 V/decade region may be indicative of a change from activation to diffusion control. Even though all 4 of these electrodes were assumed to be excessively hydrophobic, figure 16 suggests that PTFE content is still one factor to be considered for improving the O₂ evolution performance at NaₓPt₃O₂ electrodes. For example, while the 0.12 region for electrode 4 started at about 0.001 A/cm², it started at about 0.01 A/cm² for electrodes 2 and 3. The data for electrode 5, however, as discussed below, suggested that a more balanced wettability of the electrode may be more important than PTFE content alone.

O₂ evolution data were then obtained for aged electrode 5 at temperatures between 24 and 88 °C. The data for each temperature could be fitted to one straight line region with a slope of about 0.06 V/decade. A slight deviation from the 0.06 region occurred at larger current densities for each temperature as illustrated in figure 17 for data obtained at 88 °C. It is assumed that this small deviation was due to the formation of O₂ bubbles at the bottom of the electrode which became trapped inside the half-cell tube holding the electrode. The corresponding intercepts and geometric exchange current densities are listed in Table V. The doubling of the Tafel slope from 0.06 to 0.12 V/decade region was not observed for electrode 5 at larger current densities since O₂ bubble formation and mass transfer polarization limited measurements to currents of about 0.1 to 0.2 A/cm².

The O₂ evolution data for electrode 5 data for the various temperatures are shown in figure 18. The polarizations for O₂ evolution decreased with increasing temperatures indicative of an activation process. The geometric exchange current densities for O₂ evolution for electrode 5 were calculated and the corresponding logarithms were plotted in figure 19 against the reciprocals of the absolute temperatures. The "apparent" energy of activation for O₂ evolution for this region is about 9.5 kcal/mol.
O₂ evolution data for electrode 5 at 88 °C are compared in figure 20 with data reported for a similar type of PTFE-bonded NaₓPt₃O₄ electrode at 80 °C (ref. 6) and with data reported for an active NiCo₂O₄ electrode (ref. 5). Polarization values were estimated from data taken from the figure in reference 6 and these values are shown in figure 20 as triangles. The polarization for the reference 6 electrode was essentially equal to that obtained for electrode 5 for the 0.06 region. The polarization values for the NiCo₂O₄ electrode are presented in figure 20 as a dotted line with slopes of 0.06 and 0.12 V/decade. The polarization for the NiCo₂O₄ electrode is essentially equal to that of electrode 5 for the 0.06 region.

Voltage Efficiency

Although O₂ reduction and evolution reactions at NaₓPt₃O₄ are not reversible as illustrated in figure 21 for electrode 5, the PTFE-bonded gas porous diffusion NaₓPt₃O₄ electrode appears to be a viable candidate for a bifunctional O₂ electrode for a single-unit, alkaline H₂-O₂ fuel cell/electrolyzer system

Although these NaₓPt₃O₄ electrodes have not yet been fully optimized for maximum bifunctional O₂ activity, it is of interest to estimate voltage efficiencies for assumed fuel cell/electrolyzer operating conditions using Na₀.₇₅Pt₃O₄ electrode 5 as the bifunctional O₂ electrode. The iR corrected voltage efficiency, Vₑ, for the O₂ electrode may be defined as follows:

\[ Vₑ = \left( \frac{E_R}{E_O} \right) \times 100 \]  

where Eₚ is the reduction potential produced during the fuel cell operation and Eₒ is the oxidation potential required during the electrolyzer operation. Voltage efficiencies for O₂ reduction-oxidation reactions at electrode 5 may be estimated using the activation energy plots. As an illustration, geometric exchange current densities for O₂ reduction and evolution were estimated for an assumed operation at 100 °C and at geometric current densities of -0.1 A/cm² and 0.1 A/cm². These operating conditions were selected for the illustration since they represent modest goals for a single-unit fuel cell/electrolyzer system. For the case of O₂ reduction, extrapolation of the data for the 0.06 V/decade region to 100 °C (Fig. 12(a)) gives a geometric exchange current density of about 6.4x10⁻⁷ A/cm². An O₂ electrode potential of about 0.847 V is calculated for -0.1 A/cm². A corresponding potential of about 1.377 V is calculated for O₂ evolution at 0.1 A/cm². Therefore, a value of about 60 percent is estimated for the voltage efficiency (iR corrected) for 100 °C and 0.1 A/cm². For comparison, a value of about 55 percent is calculated for 25 °C and 0.1 A/cm².

NaₓPt₃O₄ Electrode Stability

The stability of electrode 5 (Na₀.₇₅Pt₃O₄) was examined at 24 °C in the presence of both N₂ and O₂. Testing under an inert atmosphere of N₂ may allow changes in the composition of Na₀.₇₅Pt₃O₄ to be seen more easily. For example, Na₀.₇₅Pt₃O₄ in the presence of O₂ is an active electrocatalyst for O₂ reduction and may mask smaller cathodic currents produced by reduction of Na₀.₇₅Pt₃O₄. For the first series of tests under N₂, a submerged sample of electrode 5 was held at 0.6 V for 7 hr at 24 °C. Cathodic currents were recorded periodically. These currents,
normalized to 1 mg of Na_{0.75}Pt_3O_4, are plotted in figure 22 against the reciprocals of the square root of time. Extrapolation to infinite time yields a value of less than 0.1 \mu A/mg of Na_{0.75}Pt_3O_4. A very small cathodic current is not an absolute indicator of the electrocatalyst's stability to electrochemical reduction. Other factors, such as delamination of the electrocatalyst from the current collector, may also lead to deceptively small currents. However, no visible changes or delamination were observed for electrode 5 after the run. Therefore, this extremely small cathodic current is assumed to represent reduction processes. The following processes may have contributed to the production of these small currents: reduction of Na_{0.75}Pt_3O_4; reduction of trace quantities of O_2 in the N_2 atmosphere; and reduction of trace impurities present in the KOH electrolyte. For example, currents of the order of 0.01 to 0.1 \mu A/mg have been observed for a Au screen current collector under similar conditions. These currents (using the Au screen) were due, presumably, to reduction of trace quantities of O_2 in the N_2 atmosphere. Therefore, it seems reasonable to assume that the cathodic current of less than 0.1 \mu A/mg (Fig. 22), is an upper limit for the corrosion current of Na_{0.75}Pt_3O_4. If this be the case, this relatively small value suggests relatively good stability for Na_{0.75}Pt_3O_4 under reducing potentials.

A second series of stability tests under flowing N_2 involved holding a sample of electrode 5 at 0.6 V for 305 hr at 24 °C with periodic interruptions for obtaining cyclic voltammograms. If electrode capacitances are obtained at potentials where reduction processes are minimal, the results may indicate whether changes in electrode surface area are occurring during the 0.6 V run. As shown in figure 7(a), the current for electrode 5 rose rapidly during the charging of the capacitance (during the anodic sweep) before leveling off to a relatively constant plateau. A similar type of curve was obtained during the cathodic sweep. The dashed lines in figure 7(a) represents the current required to charge the electrode capacitance. The small increasing currents above these plateaus are due, presumably, to small faradaic contributions. The geometric electrode capacitances, C_E, (farads/cm^2 of geometric area), using the anodic and cathodic currents at the middle of the potential sweep range (0.45 V), can be calculated as follows:

\[
C_E = 0.5 \frac{(i_A + i_C)}{R} \tag{4}
\]

where \(i_A\) and \(i_C\) are the anodic and cathodic current densities, respectively (mA/cm^2 of geometric area); and \(R\) is the sweep rate (mV/sec). A value of about 0.173 F/cm^2 was calculated for the initial cyclic sweep of electrode 5 prior to its being held at 0.6 V (fig. 7(a)). After the initial cycle sweep, electrode 5 was held at 0.6 V. The 0.6 V run was interrupted periodically for repeating the cyclic sweeps. As an illustration, the final cyclic voltammogram, obtained at the end of the 305 hr run, is shown in figure 7(b). This voltammogram was quite similar to the initial one shown in figure 7(a). The calculated geometric electrode capacitances are plotted in figure 23 against time held at 0.6 V. The capacitance values, which are related to the electrochemical surface areas of the electrode, decreased slightly during the first 20 hr after which they remained essentially constant at about 0.163 F/cm^2 for the rest of the run. This decrease in capacitance corresponds to a loss in active surface area of less than 5 percent during the first 20 hr. Therefore, it is assumed, that the change in the Na_{0.75}Pt_3O_4 electrode surface area was small and that most of the electrode structure remained relatively intact and in good contact with the current collector.

A measurement of a nonwetted sample of electrode 5 gave a value of about 1930 cm^2 of BET surface area per cm^2 of geometric surface. If this BET value is assumed for the
due to trapping, yield a relatively small decrease in electrode activity during the steady-state period. This decrease was still small, being less than 0.1 mV per cycle. The decrease was still small, being less than 0.1 mV per cycle.

The outer surface of electrode 5 was grey-black after the 305 hr run at 0.6 V. However, x-ray diffraction analysis of the electrode after the run was in good agreement with the assumption of stability of Na$_{0.75}$Pt$_3$O$_4$ under reducing potentials. For example, the analysis yielded a value of 5.672 Å for the lattice constant. Equation 1 yields a composition of about Na$_{0.79}$Pt$_3$O$_4$ indicating that little or no change in the Na content occurred during the run within the estimated limits of error of about 0.005 for the lattice constant. Furthermore, decomposition of Na$_{0.75}$Pt$_3$O$_4$ during the run to form new phases was minimal since no new phases were observed in the x-ray diffraction within the limits of detection.

Electrode 5 was examined for stability in the presence of O$_2$. The sample of electrode 5 which had been used extensively for obtaining O$_2$ reduction and evolution current-potential data was analyzed by x-ray diffraction. The analysis indicated that no new phases were produced. In addition, the Na content in the electrode remained relatively unchanged from that of an unused electrode. For example, a value of 5.676 Å was obtained for the lattice constant in the used electrode. Equation 1 yields a composition of about Na$_{0.83}$Pt$_3$O$_4$ for the used sample.

Electrode 5 was also examined for stability in the presence of O$_2$ for longer periods under both oxidizing and reducing conditions. Electrode 5 was held anodically and then cathodically for a total of 281 hr at 24 °C (fig. 24). The increase in potential during the first 121 hr at an anodic current of 0.01 A was less than 0.1 mV/hr. Upon reversal to a cathodic current of -0.01 A, the potential decreased very rapidly to the cathodic steady-state potential but then remained essentially unchanged during the next 100 hr. Upon increasing the cathodic current to -0.1 A, the potential decreased rapidly to a new steady-state potential but then remained unchanged for the additional 60 hr. Therefore, relatively good stability is assumed for Na$_{0.75}$Pt$_3$O$_4$ for long periods of O$_2$ reduction and evolution. X-ray diffraction analysis of electrode 5 after the 281 hr test was in agreement with this assumption. For example, a value of 5.676 Å was obtained for the lattice constant indicating that the composition remained essentially unchanged.

For another series of tests under flowing O$_2$, electrode 5 was cycled at 0.01 and -0.01 A/cm$^2$ for alternate periods of 24 hr for a total of about 340 hr. The results are shown in figure 25. While the potentials appeared to increase slightly during each anodic 24 hr period, these potentials at the end of each anodic period were essentially the same value. For the cathodic 24 hr periods, the reverse appeared to be true. For example, the cathodic potentials remained essentially unchanged during each 24 hr period but decreased slightly after each previous anodic period. This decrease was still small, being less than 1 mV per cycle.

An electrode may be exposed to many oxidation and reduction potentials under O$_2$ during a moderate time period by continuous cycling. Electrode 5 was cycled continuously between 0.827 and 1.446 V at a scan rate of 1 mV/sec (fig. 21). The potential of 1.446 V was chosen to yield a relatively small anodic current of about 0.01 A/cm$^2$ which minimizes anodic polarization due to trapping of O$_2$ bubbles inside the electrode holder. Prior to the initiation of the cycling, the steady-state cathodic current at 0.827 V was determined to be -0.073 A. Changes in electrode activity during cycling may be determined by interrupting the cycling periodically and redetermining the steady-state cathodic currents at 0.827 V. These currents and iR
polarizations decreased slightly as the cycling proceeded. The slope for O₂ reduction, using the Tafel polarization plot in this region, was determined previously to be 0.04 V/decade. Each potential was then normalized by calculating the polarization potential that is necessary to restore the measured current to the initial current of -0.073 A. The normalized potentials (iR corrected) are plotted in figure 26 against the number of cycles. This decrease in potential was less than 10 μV/cycle suggesting relatively good NaₓPt₃O₄ stability. X-ray diffraction analysis was in good agreement with this assumption. For example, analysis of electrode 5 after 1132 cycles (390 hr) indicated that the composition of the electrode remained relatively unchanged. A value of 5.677 Å was obtained for the lattice constant yielding a composition of about Na₀.₈₄Pt₃O₄.

CONCLUDING REMARKS

1. The present study suggests that the PTFE-bonded NaₓPt₃O₄ gas porous diffusion electrode may be a viable electrocatalyst candidate for bifunctional O₂ reduction and evolution activity. The following results support this conclusion:

a. The NaₓPt₃O₄ electrodes exhibited promising Tafel slopes of about 0.06 V/decade for both O₂ reduction and evolution at moderate current densities. "Apparent" activation energy values of about 5.6 and 9.5 Kcal/mol were calculated for O₂ reduction and evolution, respectively.

b. O₂ reduction polarization for partially optimized electrode 5 was only somewhat larger than that reported for an IFC Au-10 percent Pt fuel cell O₂ electrode. O₂ evolution polarization for electrode 5 was similar to that reported for the active NiCo₂O₄ electrolysis electrode.

c. For O₂ reduction, the 0.06 slope doubled to about 0.12 V/decade at larger current densities indicative of a change from activation to diffusion control for the gas porous diffusion electrodes examined. Further improvement in electrode performance may be possible if a more complete optimization of the electrode structure is accomplished.

d. Voltage efficiencies of about 60 and 55 percent were estimated for O₂ reduction-oxidation processes at electrode 5 at 100 and 25 °C, respectively, for assumed anodic and cathodic current densities of -0.1 and 0.1 A/cm².

2. Stability testing at 24 °C suggests that NaₓPt₃O₄ electrodes are relatively stable at reducing and oxidizing potentials that might be encountered at the O₂ electrode in a fuel cell/electrolyzer system. The following results support this conclusion:

a. The corrosion current for electrode 5 (Na₀.₇₅Pt₃O₄) at 0.6 V under N₂ was less than 0.1 μA/mg of Na₀.₇₅Pt₃O₄.

b. While the electrode was being held at 0.6 V under N₂, the electrode capacitance of electrode 5 decreased less than 5 percent during the first 20 hr but then remained essentially constant for the remainder of the 305 hr test period.

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c. The respective steady-state potentials of electrode 5 under O₂ were relatively constant at an anodic current of 0.01 A/cm² for 121 hr and at cathodic currents of -0.01 A/cm² for 100 hr and -0.1 A/cm² for 60 hr.

d. The respective steady-state potentials of electrode 5 under O₂ were relatively constant during cycling for 24 hr periods at alternate anodic and cathodic current densities of 0.01 and -0.01 A/cm² for a testing period of 340 hr.

e. The steady-state potentials of electrode 5 under O₂ were relatively constant at -0.073 A during continuous cycling between reducing and oxidizing potentials of 0.827 and 1.446 V, respectively, for a testing period of 1132 cycles (390 hr).

f. X-ray diffraction analyses indicated that secondary phases were not produced and that the Na content remained essentially unchanged during each of the stability testing runs.

3. Additional optimization of PTFE-bonded NaₓPt₃O₄ electrodes is warranted since the partially optimized Na₀.₇₅Pt₃O₄ electrode 5 showed better bifunctional activity and stability than has been reported for any substance. Suggestions for further work are:

a. The effect of varying Na content (X = 0.7 to 1) in the NaₓPt₃O₄ powders upon activity and stability should be examined.

b. NaₓPt₃O₄ powders with surface areas greater than 20 m²/g should be prepared. Improved morphology and particle size distribution of these powders is also desirable. For example, preparation from fine particle precursors may be very useful.

c. The effect of PTFE content should be examined in greater detail. For example, preliminary results for electrodes 1, 2, 3 and 4, which may have been too hydrophobic in character, suggested that maximum bifunctional O₂ activity may require an intermediate PTFE content. The effect of PTFE content upon electrode stability was not examined in the present study.

d. Catalyst and electrode processing should be critically investigated. Catalyst/PTFE processing and electrode fabrication conditions are important factors for optimizing the hydrophobic/hydrophilic character of the electrode and also for obtaining stable bonding of the electrocatalyst layer to the current collector. Furthermore, electrodes optimized for O₂ reduction may require different catalyst/PTFE processing conditions than required for O₂ evolution.

REFERENCE


### TABLE I.—PTFE-BONDED Na₅Pt₃O₄ ELECTRODES

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Na₀.₈₀Pt₃O₄ content, mg/cm²</th>
<th>Na₀.₇₅Pt₃O₄ content, mg/cm²</th>
<th>PTFE content, percent of Na₅Pt₃O₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>----</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>13.6</td>
<td>----</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>----</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>----</td>
<td>24.5</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>----</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

### TABLE II.—O₂ REDUCTION AT Na₅Pt₃O₄ ELECTRODES 1, 2, 3 AND 4

#### (a) 0.06 V/Decade region

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm² (normalized to 20 mg/cm²)</th>
<th>Geometric current density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6014</td>
<td>1.1x10⁻¹⁰</td>
<td>0.0001 to 0.0008</td>
</tr>
<tr>
<td>2</td>
<td>0.5386</td>
<td>1.6x10⁻⁹</td>
<td>0.0001 to 0.001</td>
</tr>
<tr>
<td>3</td>
<td>0.4540</td>
<td>2.7x10⁻⁸</td>
<td>0.0001 to 0.0012</td>
</tr>
<tr>
<td>4</td>
<td>0.4819</td>
<td>7.6x10⁻⁹</td>
<td>0.0008 to 0.004</td>
</tr>
</tbody>
</table>

#### (b) 0.12 V/Decade region

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric current density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7834</td>
<td>3.5x10⁻⁷</td>
<td>0.0008 to 0.0016</td>
</tr>
<tr>
<td>2</td>
<td>0.7202</td>
<td>1.5x10⁻⁶</td>
<td>0.001 to 0.0025</td>
</tr>
<tr>
<td>3</td>
<td>0.6286</td>
<td>5.8x10⁻⁶</td>
<td>0.0012 to 0.005</td>
</tr>
<tr>
<td>4</td>
<td>0.6275</td>
<td>4.8x10⁻⁶</td>
<td>0.004 to 0.010</td>
</tr>
</tbody>
</table>
### TABLE III.—O₂ REDUCTION AT Na₀.₇₅Pt₃O₄ ELECTRODE 5

(a) 0.04 V/Decade region

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric current density range, A/cm²</th>
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</thead>
<tbody>
<tr>
<td>24</td>
<td>0.3899</td>
<td>1.8x10⁻¹⁰</td>
<td>0.002 to 0.025</td>
</tr>
<tr>
<td>33</td>
<td>0.3827</td>
<td>2.7x10⁻¹⁰</td>
<td>0.002 to 0.025</td>
</tr>
<tr>
<td>50</td>
<td>0.3692</td>
<td>5.9x10⁻¹⁰</td>
<td>0.001 to 0.025</td>
</tr>
<tr>
<td>71</td>
<td>0.3567</td>
<td>1.2x10⁻⁹</td>
<td>0.0015 to 0.032</td>
</tr>
<tr>
<td>80</td>
<td>0.3536</td>
<td>1.5x10⁻⁹</td>
<td>0.0015 to 0.040</td>
</tr>
<tr>
<td>93</td>
<td>0.3524</td>
<td>1.6x10⁻⁹</td>
<td>0.001 to 0.050</td>
</tr>
</tbody>
</table>

(b) 0.06 V/Decade region

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric current density range, A/cm²</th>
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<tbody>
<tr>
<td>24</td>
<td>0.4218</td>
<td>9.3x10⁻⁸</td>
<td>0.025 to 0.125</td>
</tr>
<tr>
<td>33</td>
<td>0.4149</td>
<td>1.2x10⁻⁷</td>
<td>0.025 to 0.125</td>
</tr>
<tr>
<td>50</td>
<td>0.4038</td>
<td>1.9x10⁻⁷</td>
<td>0.025 to 0.125</td>
</tr>
<tr>
<td>71</td>
<td>0.3877</td>
<td>3.5x10⁻⁷</td>
<td>0.032 to 0.160</td>
</tr>
<tr>
<td>80</td>
<td>0.3810</td>
<td>4.5x10⁻⁷</td>
<td>0.040 to 0.200</td>
</tr>
<tr>
<td>93</td>
<td>0.3774</td>
<td>5.1x10⁻⁷</td>
<td>0.050 to 0.160</td>
</tr>
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(c) 0.12 V/Decade region

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric current density range, A/cm²</th>
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<td>24</td>
<td>0.4775</td>
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<td>0.125 to 0.320</td>
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<td>0.4681</td>
<td>1.3x10⁻⁴</td>
<td>0.125 to 0.320</td>
</tr>
<tr>
<td>50</td>
<td>0.4526</td>
<td>1.7x10⁻⁴</td>
<td>0.125 to 0.320</td>
</tr>
<tr>
<td>71</td>
<td>0.4343</td>
<td>2.4x10⁻⁴</td>
<td>0.160 to 0.400</td>
</tr>
<tr>
<td>80</td>
<td>0.4222</td>
<td>3.0x10⁻⁴</td>
<td>0.200 to 0.400</td>
</tr>
<tr>
<td>93</td>
<td>0.4226</td>
<td>3.0x10⁻⁴</td>
<td>0.160 to 0.400</td>
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</table>
TABLE IV.—O₂ EVOLUTION AT NaₓPt₃O₄ ELECTRODES 1, 2, 3 and 4

(a) 0.04 V/Decade region

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm² (normalized to 20 mg/cm²)</th>
<th>Geometric exchange density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.2692</td>
<td>2.7x10⁻⁷</td>
<td>0.0002 to 0.003</td>
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</table>

(b) 0.06 V/Decade region

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric exchange density range, A/cm²</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>0.3290</td>
<td>3.9x10⁻⁶</td>
<td>0.001 to 0.025</td>
</tr>
<tr>
<td>2</td>
<td>0.3192</td>
<td>7.0x10⁻⁶</td>
<td>0.003 to 0.020</td>
</tr>
<tr>
<td>3</td>
<td>0.3010</td>
<td>9.6x10⁻⁶</td>
<td>0.0001 to 0.0004</td>
</tr>
<tr>
<td>4</td>
<td>0.2703</td>
<td>2.6x10⁻⁵</td>
<td>0.0006 to 0.0015</td>
</tr>
</tbody>
</table>

(c) 0.12 V/Decade region

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric exchange density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4240</td>
<td>3.5x10⁻⁴</td>
<td>0.025 to 0.125</td>
</tr>
<tr>
<td>2</td>
<td>0.4213</td>
<td>4.5x10⁻⁴</td>
<td>0.020 to 1.160</td>
</tr>
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<td>3</td>
<td>0.5054</td>
<td>6.1x10⁻⁵</td>
<td>0.0004 to 0.025</td>
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<td>4</td>
<td>0.4394</td>
<td>1.8x10⁻⁴</td>
<td>0.0015 to 0.005</td>
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TABLE V.—O₂ EVOLUTION AT Na₀.₇₅Pt₉O₄ ELECTRODE 5 FOR THE 0.06 V/DECADE REGION

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Intercept, V</th>
<th>Geometric exchange current density, A/cm²</th>
<th>Geometric exchange density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.3616</td>
<td>9.4x10⁻⁷</td>
<td>0.001 to 0.013</td>
</tr>
<tr>
<td>37</td>
<td>0.3423</td>
<td>2.0x10⁻⁶</td>
<td>0.001 to 0.025</td>
</tr>
<tr>
<td>49</td>
<td>0.3241</td>
<td>4.0x10⁻⁶</td>
<td>0.001 to 0.040</td>
</tr>
<tr>
<td>63</td>
<td>0.3078</td>
<td>7.4x10⁻⁶</td>
<td>0.001 to 0.025</td>
</tr>
<tr>
<td>76</td>
<td>0.2914</td>
<td>1.4x10⁻⁵</td>
<td>0.001 to 0.020</td>
</tr>
<tr>
<td>88</td>
<td>0.2909</td>
<td>1.4x10⁻⁵</td>
<td>0.001 to 0.032</td>
</tr>
</tbody>
</table>
Figure 1.—Schematic of floating electrode half-cell apparatus.

Figure 2.—Hg/HgO reference electrode potential with temperature (-0.45 mV/°C, 1 atm O₂, 30% KOH).

Figure 3.—IR polarization with current during O₂ reduction of electrode 5.

Figure 4.—Erratic polarization during O₂ evolution at electrode 5 (0.1 A/cm², 24 °C).

Figure 5.—Reduction aging of preconditioned electrode 5 at -0.01 A/cm² (24 °C).

Figure 6.—Cyclic voltammogram of electrode 5 (0.3-1.4 V, 1 mV/sec, N₂, 24 °C, submerged).
Figure 7.—Cyclic sweep of electrode 5 (0.4 to 0.5 V, 1 mV/sec, N₂, 24 °C, submerged).

(b) Cyclic sweep after 305 hr at 0.6 V.

Figure 8.—Tafel plot for O₂ reduction at electrode 3 (80 °C, 1 atm O₂, 30% KOH).
Figure 9.—Tafel plots for $O_2$ reduction at electrodes 1, 2, 3 and 4: normalized to 20 mg/cm$^2$ (80 °C, 1 atm $O_2$, 30% KOH).

Figure 10.—Tafel plot for $O_2$ reduction at electrode 5 at 24 °C (electrode 3 at 80 °C, 1 atm $O_2$, 30% KOH).

Figure 11.—Tafel plots for $O_2$ reduction at electrode 5 at various temperatures (1 atm $O_2$, 30% KOH).
Figure 12.—“Apparent” activation energy plot for O₂ reduction at electrode 5 (1 atm O₂, 30% KOH).

Figure 13.—Comparison of O₂ reduction polarization (80 °C, 1 atm O₂, 30% KOH).
Figure 14.—Tafel plot for $O_2$ evolution at electrode 1 (80 °C, 1 atm $O_2$, 30% KOH).

Figure 15.—Tafel plot for $O_2$ evolution at electrode 2 (80 °C, 1 atm $O_2$, 30% KOH).

Figure 16.—Tafel plots for $O_2$ evolution at electrodes 1, 2, 3 and 4: normalized to 20 mg/cm² (80 °C, 1 atm $O_2$, 30% KOH).

Figure 17.—Tafel plot for $O_2$ evolution at electrode 5 (80 °C, 1 atm $O_2$, 30% KOH).
Temperature
°C

24
37
49
63
76
88

Figure 18.—Tafel plot for O₂ evolution at electrode 5 at various temperatures (1 atm O₂, 30% KOH).

Figure 19.—"Apparent" activation energy plot for O₂ evolution at electrode 5 for the 0.06 V/decade region (1 atm O₂, 30% KOH).

Figure 20.—Comparison of O₂ evolution polarization (80 °C, 1 atm O₂, 30% KOH).

Figure 21.—Cyclic voltammogram of electrode 5 between 0.827 and 1.446 V at 1 mV/sec (24 °C, 1 atm O₂, 30% KOH).
Figure 22.—Cathodic corrosion current for electrode 5 at 0.6 V (24 °C, 1 atm N₂, electrode submerged in 30% KOH).

Figure 23.—Capacitance at 0.45 V with time for electrode 5 held at 0.6 V (voltammogram between 0.4 and 0.5 V at 1 mV/sec, 24 °C, 1 atm N₂).

Figure 24.—Stability testing of electrode 5 held at anodic and cathodic potentials (24 °C, 1 atm O₂).

Figure 25.—Stability testing of electrode 5 during cycling at anodic 0.01 and cathodic -0.01 A/cm² (24 °C, 1 atm O₂).

Figure 26.—Normalized potential of electrode 5 at -0.073 A with cycling between 0.827 and 1.446 V at 1 mV/sec (24 °C, 1 atm O₂).
The present study suggests that PTFE-bonded Na$_x$Pt$_3$O$_4$ gas porous diffusion electrodes may be a viable candidate for bifunctional O$_2$ reduction and evolution activity. The electrodes exhibited Tafel slopes of about 0.06 V/decade for both O$_2$ reduction and evolution. For O$_2$ reduction, the 0.06 slope doubled to 0.12 V/decade at larger current densities. Preliminary stability testing at 24 °C suggested that the Na$_x$Pt$_3$O$_4$ electrodes were relatively stable at reducing and oxidizing potentials typically encountered at the O$_2$ electrode in a regenerative fuel cell.